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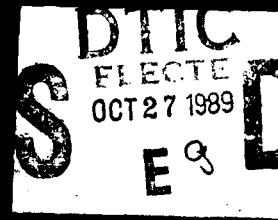
AD-A214 061

NCT Report No 3789/607

Advanced Tribological  
Coatings For High Specific  
Strength Alloys,  
R&D 5876-MS-01

Contract DAJ A45-87-C-004

5th Interim Report



# National Centre of Tribology

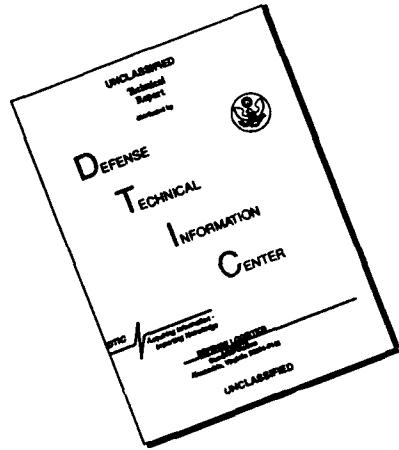
Risley Nuclear Power  
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NCT

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Prepared for: US Army Research, Development &  
Standardisation Group  
Fiscal Office  
223, Old Marylebone Road  
LONDON  
NW1 5TH

Date: 29 September 1989

Our Ref : 1610/5525

Your Ref: AMXSN-UK-FO/R&D-5876-MS-01(70-1F)

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5th Interim Report

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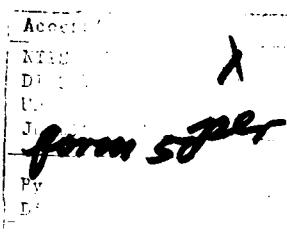
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89 10 27 049

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A-1 93 QM

## 1. INTRODUCTION

This 5th interim report summarises the work performed to date on the US Army contract 'Advanced Tribological Coatings for High Specific Strength Substrates'. The objective of this contract are to develop and test a surface treatment suitable for the hardening of a titanium alloy precision gear for use in a vacuum environment.

Attention has been primarily directed at surface hardening by the interstitial diffusion of the elements nitrogen, oxygen and carbon. Targets of a surface hardness of >500 HV and depth 50 microns, without the need of any post heat treatment operations have been identified.

## 2. SURFACE TREATMENTS

The surface treatments under study have been applied to specimens of IMI 318 (Ti6Al4V), cut from plate. The sample numbers and corresponding surface treatments which have been carried out and tested to date are listed in Table 1 below. 'SHT' indicates that the plates sample was in a solution heat treated condition before surface treatment. 'H&G' indicates that the sample was in a hardened and ground condition before surface treatment.

*Surface treatments: Aluminothermic Nitriding  
Diffusion, Frictional, FGD, Gaseous  
Plating*

Table 1: Sample Number Allocated to Surface Treatments.

Sample Number	Surface Treatment
HSSA1	Solution Heat Treated
HSSA2	Hardened and Ground
HSSA3	(SHT) Plasma Nitrocarburized 1
HSSA4	(SHT) Beta Nitrocarburized
HSSA5	(SHT) Ion Implanted (N <sup>+</sup> ) 1
HSSA6	(H&G) Ion Implanted (N <sup>+</sup> ) 2
HSSA7	(SHT) Hard Anodised 1
HSSA8	(H&G) Hard Anodised 2
HSSA9	(SHT) Plasma Nitrocarburized 2
HSSA10	(SHT) Hard Anodised 3
HSSA11	(H&G) Hard Anodised 4
HSSA12	(SHT) Plasma Nitrided 1
HSSA13	(H&G) Plasma Nitrided 2
HSSA14	(SHT) High Temperature Nitrocarburized 1
HSSA15	(H&G) Nitrox 1
HSSA16	(SHT) Pack Aluminising 1
HSSA17	(SHT) Nitrox 2
HSSA18	(H&G) Nitrox 3
HSSA19	(SHT) Pack Aluminising 2
HSSA20	(SHT) Gas Carbonitriding 1
HSSA21	(SHT) Diamond-like Carbon (DLC) 1
HSSA22	(SHT) TiN Reactive Sputter
HSSA23	(SHT) TiN/HfN Multilayer
HSSA24	(SHT) Pack Aluminising 3

### 3. SURFACE ROUGHNESS MEASUREMENTS

For the application of dry lubricants (ie sputtered MoS<sub>2</sub>) onto hardened titanium alloy gears, the surface roughness is an important parameter in determining film (and hence gear life). The surface roughness of all the sample plates were, therefore, measured using a Talysurf 6 profilometer, and the values of Ra, Delta-Q and R<sub>sk</sub> recorded. These parameters are defined as:

Ra: The arithmetic mean of the departure of the roughness profile from the mean line (in micrometres).

Delta-Q: The RMS slope of the profile throughout the assessment length (in degrees).

R<sub>sk</sub>: The measure of the symmetry of the profile about the mean line (in degrees). R<sub>sk</sub> will distinguish between asymmetric profiles which have the same Ra value.

The surface roughness measurements for the samples are summarised in Figure 1. This figure has been arranged with the samples that were originally solution heat treated grouped first, followed by those which were originally hardened and ground. Essentially only pack aluminising (HSSA19) causes any detriment to the surface roughness, all other treatments either cause no change or a small improvement in the surface roughness.

### 4. METALLOGRAPHIC EXAMINATION

Optical metallographic specimens were prepared by nickel coating a small piece of each sample and embedding this in thermosetting resin. Each specimen was then ground and polished to produce a section through the sample at 90° to the hardened surface. From this section, coating structure and thickness could be ascertained, and a microhardness depth profile measured.

#### 4.1 Coating Thickness

The micrographs from the metallographic examination of the samples, with the exception of HSSA10 are included in Appendix 2. From the micrographs the resulting coating thickness was determined and are given in table 2 below.

Table 2: Surface Treatment Coating Thickness & Hardness.

Sample	Surface Treatment	Coating Thickness	Hardness
HSSA1	Solution Heat Treated	not applicable	
HSSA2	Hardened and Ground	not applicable	
HSSA3	Plasma Nitrocarburized 1	<2 micrometres	Not measured
HSSA4	Beta Nitrocarburized	5-10 micrometres	550 Hv
HSSA5	Ion Implanted (N <sup>+</sup> ) 1	negligible	Not measured
HSSA6	Ion Implanted (N <sup>+</sup> ) 2	negligible	Not measured
HSSA7	Hard Anodised 1	negligible	Not measured
HSSA8	Hard Anodised 2	negligible	Not measured
HSSA9	Plasma Nitrocarburized 2	negligible	Not measured
HSSA10	Hard Anodised 3	negligible	Not measured
HSSA11	Hard Anodised 4	negligible	Not measured
HSSA12	Plasma Nitrided 1	<1 micrometre	Not measured
HSSA13	Plasma Nitrided 2	negligible	Not measured
HSSA14	High Temp Nitrocarburized	<2 micrometres	Not measured
HSSA15	Nitrox 1	.5 micrometres	-400 Hv
HSSA16	Pack Aluminising 1	25 micrometres	360 Hv
HSSA17	Nitrox 2	negligible	Not measured
HSSA18	Nitrox 3	low micrometres	-400 Hv
HSSA19	Pack Aluminising 2	25 micrometres	<400 Hv
HSSA20	Gas Carbonitriding 1	50 micrometres	700 Hv
HSSA21	Diamond-like Carbon 1	1 micrometre	Not measured
HSSA22	TiN Reactive Sputter	3 micrometres	Not measured
HSSA23	TiN/HfN Multilayer	5 micrometres	Not measured
HSSA24	Pack Aluminising 3	27 micrometres	560 Hv

#### 4.2 Microhardness Depth Profile

Microhardness depth profiles were produced by measuring the Vickers microhardness at increasing depth into the sample on the metallographic specimens. The hardness was measured by applying a load of 50N for 15 seconds. The microhardness profiles are summarised in Appendix 3.

## 5. FRICTION AND WEAR MEASUREMENTS

To identify the most promising surface treatments from the large number of samples (for more detailed friction & wear evaluation in vacuum and for rolling contact surface fatigue assessment), the friction and wear of all samples was evaluated at two load conditions on a reciprocating tribometer at NCT. All these 'screening' tests were performed in air; any sample performing poorly in air would be very unlikely to perform well under vacuum conditions.

### 5.1 Test Conditions

The reciprocating tribometer was set to give a 20 mm stroke, with 500 cycles per test, giving a cumulative sliding distance of 20 metres. Tests were performed at two different loads (20 & 50N, equivalent to maximum Hertzian contact stresses of 1.30 & 1.76 MPa respectively). The loads were applied using hardened En31 steel balls in contact with the treated titanium alloy plate. Both balls and plate samples were ultrasonically cleaned before test and no lubricant was added. Frictional forces were recorded continuously on a chart recorder.

Wear profiles and the volume of material removed from the specimens was measured using a 3D surface profilometer. All the wear scars were photographed at x50 in a SEM at 20kV using Secondary Electron Imaging (SEI), with additional photographs taken as needed at other magnifications and accelerating voltages, using both SEI and Back Scattered Imaging (BSI).

### 5.2 Results at 20N Load

Figures 2 and 3 summarise the friction (at various test intervals) and the measured wear rates. The wear profiles, with attached SEM micrographs of the central region of the scars, with the exception of HSSA16, are contained in Appendix 4.

Samples HSSA1 & HSSA2 can be regarded as the baseline performance, any coating exhibiting high friction or wear can be rejected from further study. At this load samples HSSA4, HSSA10, HSSA11, HSSA14, HSSA20 to HSSA 23 show 'good' performance. The extent of the wear on HSSA4, HSSA20 and HSSA24 is not readily apparent in the micrographs attached to the wear profiles. The scars show up more clearly when viewed in back

scattered image (Figure 4). The TiN/HfN multilayer coating of HSSA23 appears to have started to break up during this test (Figure 5).

### 5.3 Results at 50N Load

Figures 6 and 7 show the friction (at various test intervals) and the measured wear rates. The wear profiles, with attached SEM micrographs of the central region of the scars, with the exception of HSSA16, are contained in Appendix 5.

Samples HSSA4, HSSA14, HSSA20 & HSSA 22 give low wear rates and reasonable friction coefficients. SEM analysis revealed metal transfer from the En 31 ball to the plate occurred during the test on HSSA4 (Figure 8). A small hole can be seen in the coating of sample HSSA 22 which may indicate that the coating is starting to break up (Figure 9).

### 6. DISCUSSION & FURTHER WORK PLANNED

To date samples HSSA4, HSSA14, HSSA20 & HSSA22 show the most promising friction and wear performance. Sample HSSA20 also meets the targets for surface hardness and treatment depth

Analysis of the plasma nitrided samples (HSSA12 and HSSA13) has revealed poor processing, further samples are being prepared with a different supplier. The TiN/HfN multilayer (HSSA23) probably failed at 50N because substrate could not support the coating (cf ice on mud). The wear rate for this treatment is greater than that for uncoated titanium because of the presence of TiN and HfN particles in the wear debris. These are very hard and effectively improve the cutting properties of the En30 ball. Multi-treatment (e.g. Nitrocarburize then TiN/HfN multilayer) would result in support for the film and improved results. This approach is being evaluated.

Further work is aimed at measuring the friction and wear performance of samples HSSA1, HSSA2, HSSA4, HSSA14, HSSA20 and HSSA22 at a load of 250N (3 GPa). This is the maximum achievable on the NCT reciprocating tribometer.

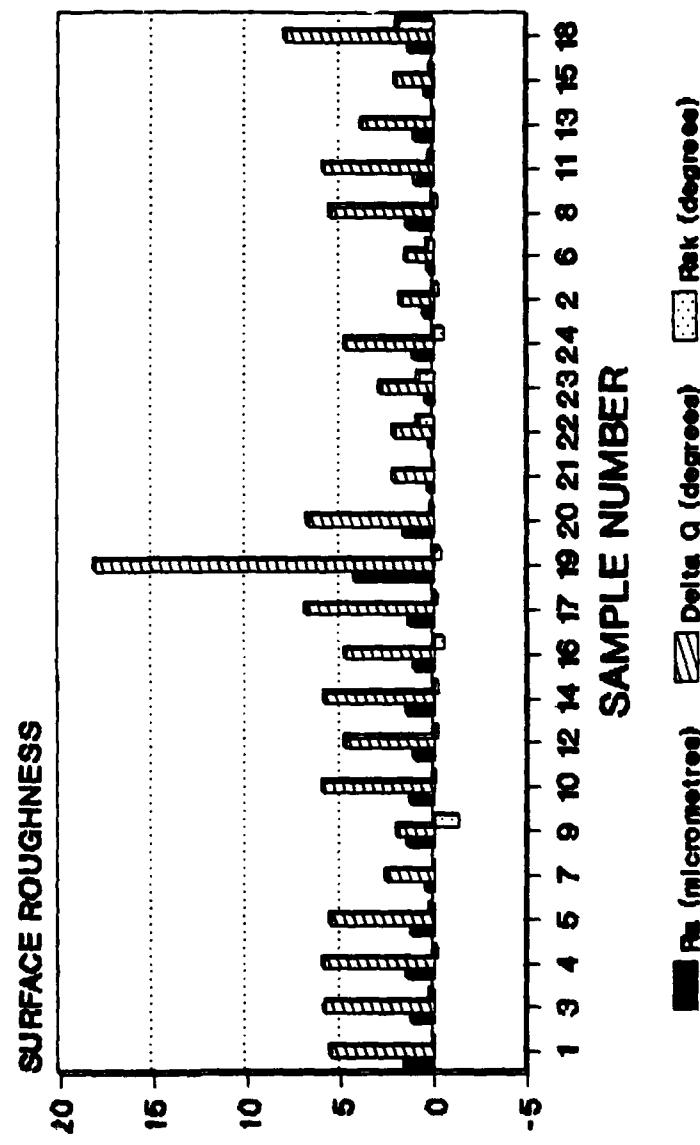
Sample HSSA26 (High Temperature Plasma Nitriding) has recently arrived, and is currently undergoing metallographic examination. The remaining samples are still with the

coating/surface treatment companies.

All test items for the NCT vacuum test rig and rolling contact fatigue specimens have been manufactured. After completion of the 250N tests, the fatigue specimens will be sent for treatment and then forwarded to AMTL for evaluation.

## HSSA RECIPROCATING WEAR TESTS

### SURFACE ROUGHNESS MEASUREMENTS

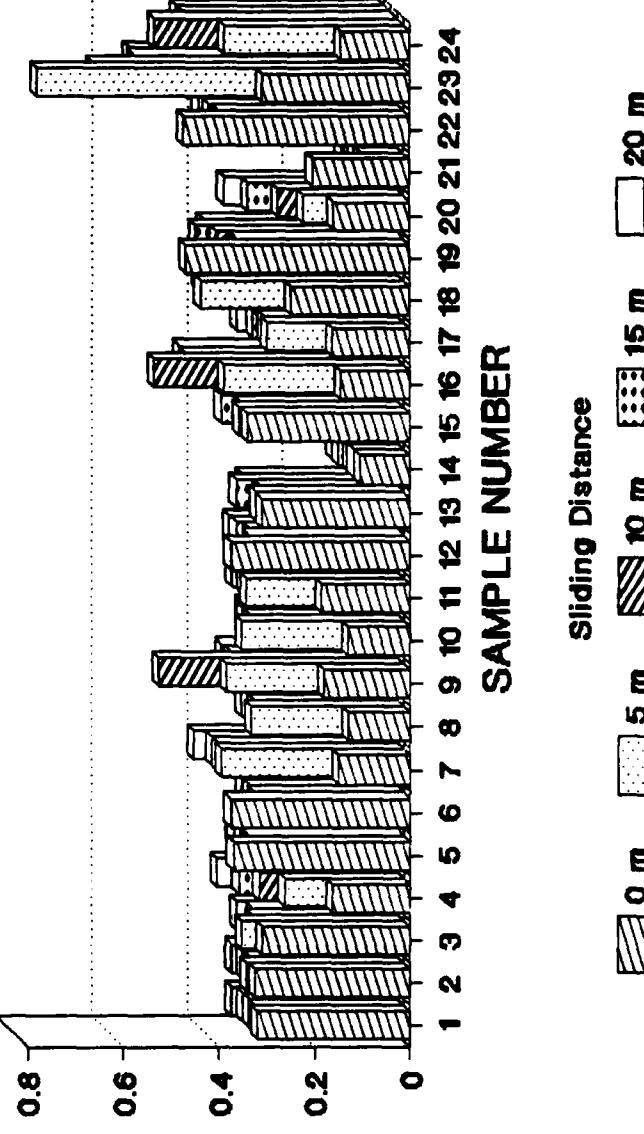


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## HSSA RECIPROCATING WEAR TESTS

20 N LOAD, IN AIR, 1.3 GPa (MAX)

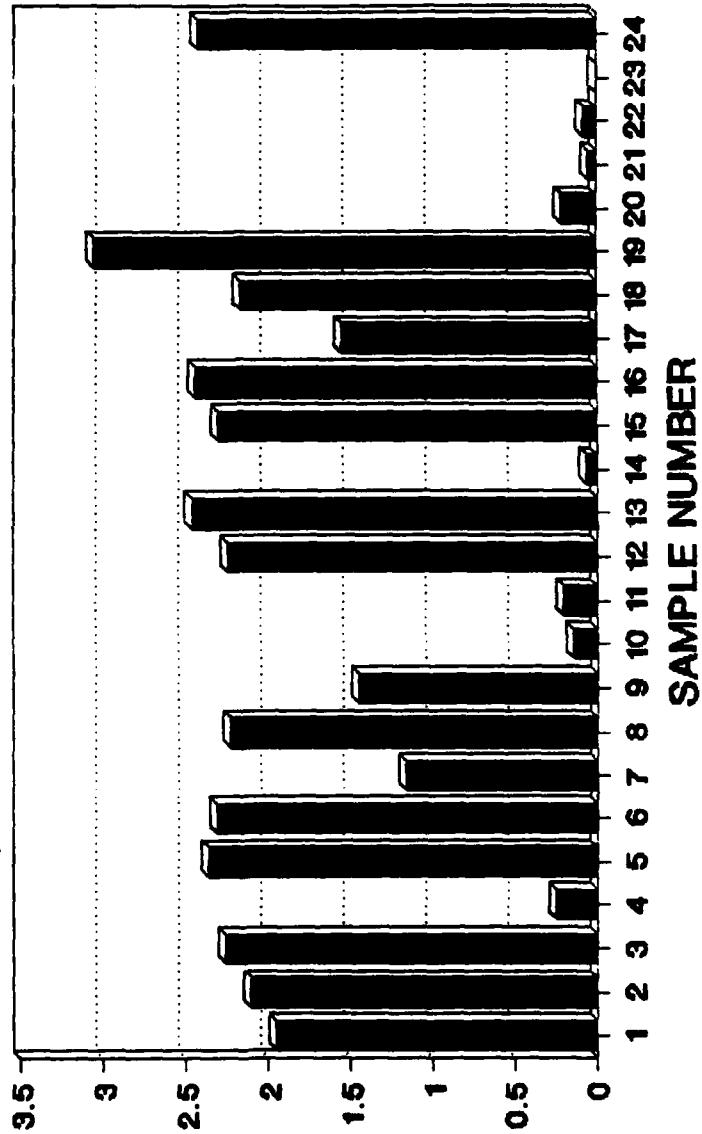
FRICITION COEFFICIENT



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**HSSA RECIPROCATING WEAR TESTS**  
20 N LOAD, IN AIR, 1.3 GPa (MAX)

WEAR RATE ( $m^{-3}/m/N \times 10^{-13}$ )



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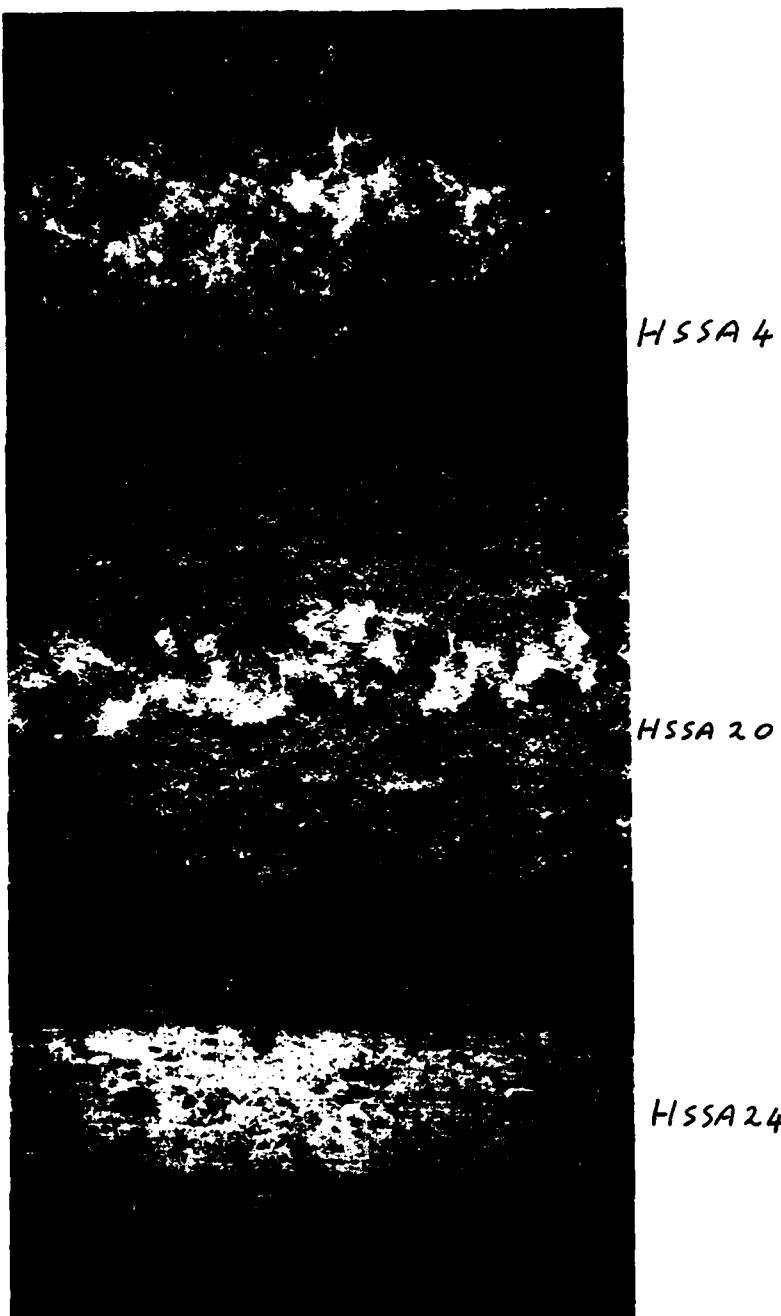


Figure 4:  $\times 50$ , 20kV Accelerating Voltage  
Back Scattered Image

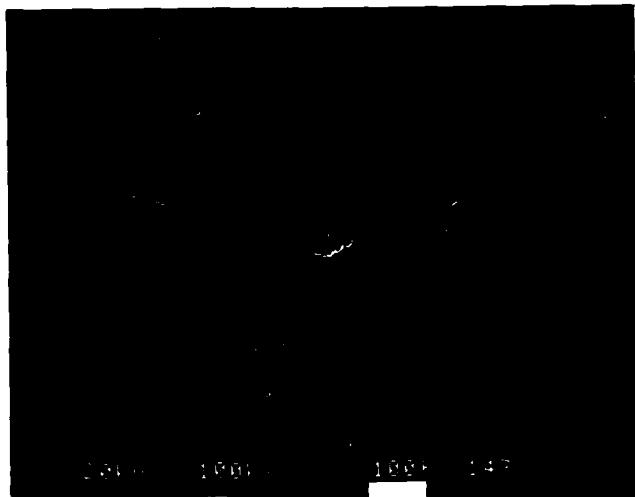
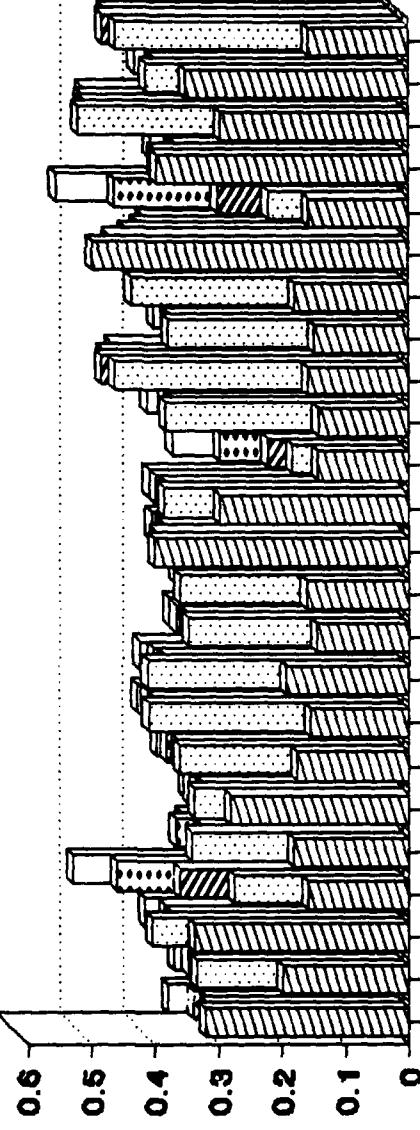


Figure 5: HSSA23: Coating damage at 20N load.

**HSSA RECIPROCATING WEAR TESTS**  
**50 N LOAD, IN AIR, 1.76 GPa (MAX)**

FRICITION COEFFICIENT



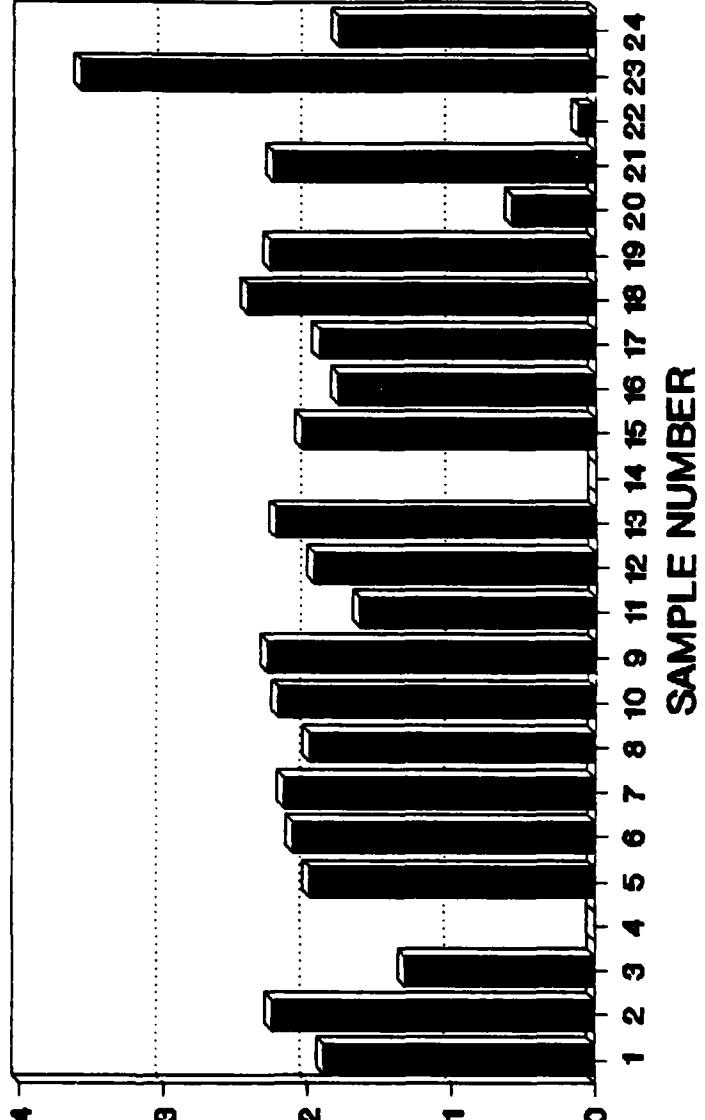
Sliding Distance

0 m    5 m    10 m    15 m    20 m

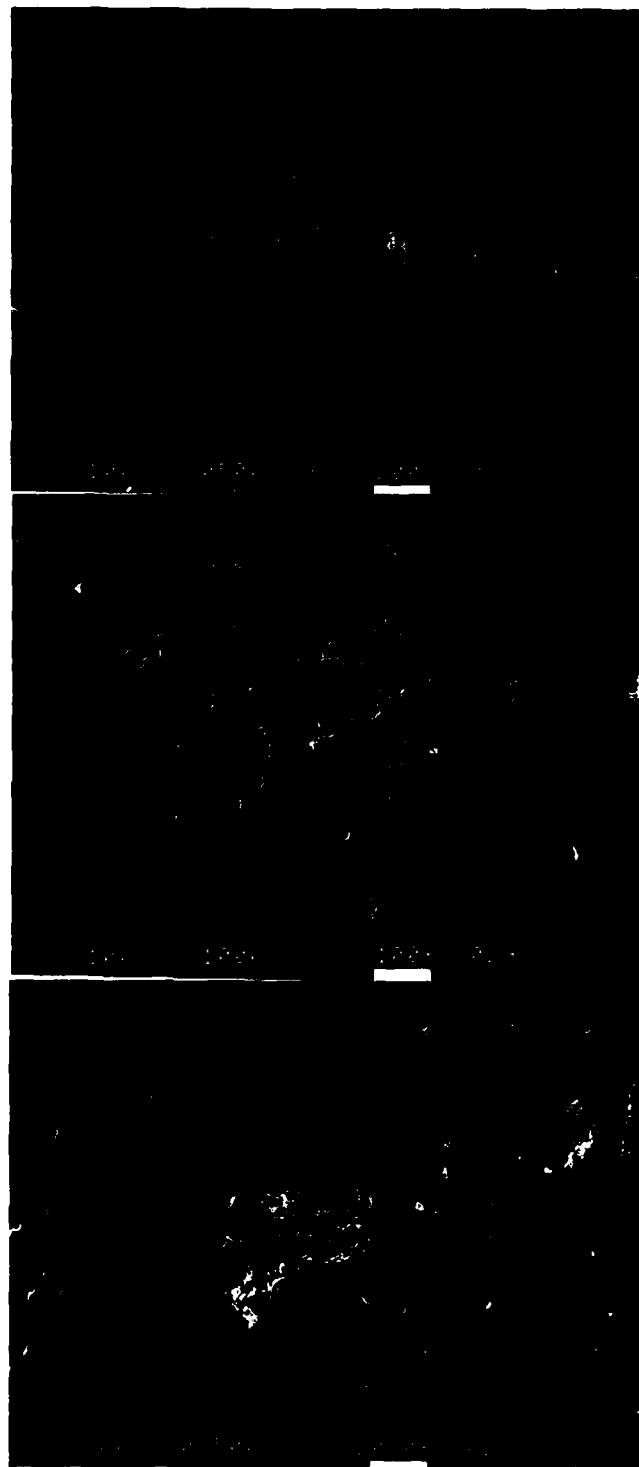
NATIONAL CENTRE OF TRIBOLOGY

**HSSA RECIPROCATING WEAR TESTS**  
50 N LOAD, IN AIR, 1.76 GPa (MAX)

WEAR RATE ( $m^3/m/N \times 1E-13$ )

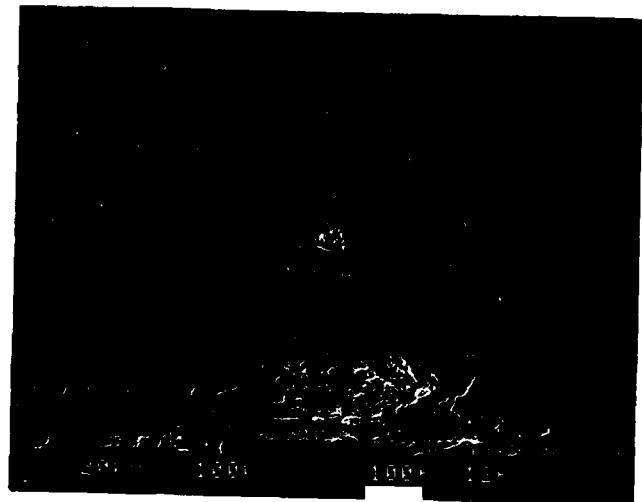


NATIONAL CENTRE OF TRIBOLOGY



Back-scattered  
Image

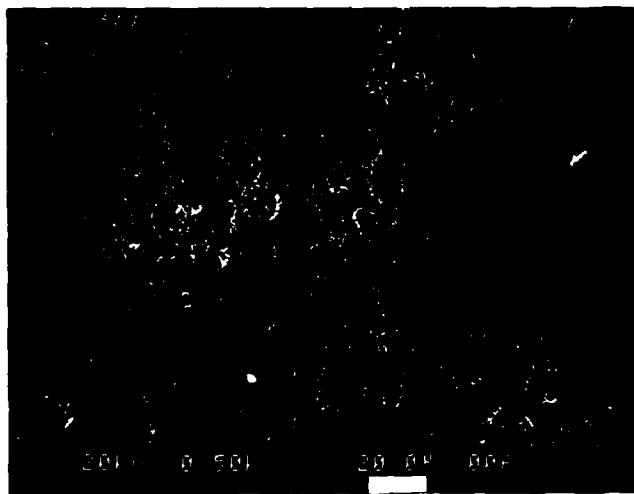
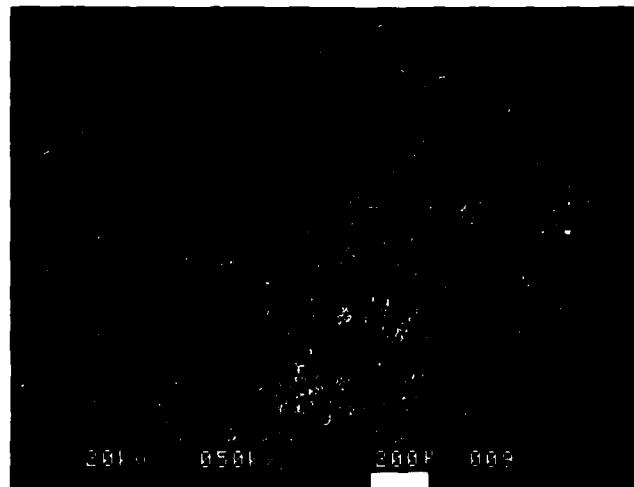
Figure 8: HSSA4, 10kV Accelerating Voltage, Showing Metal Transfer.



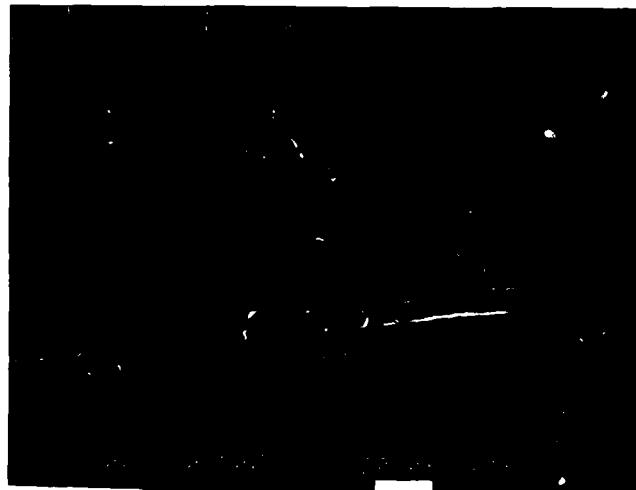
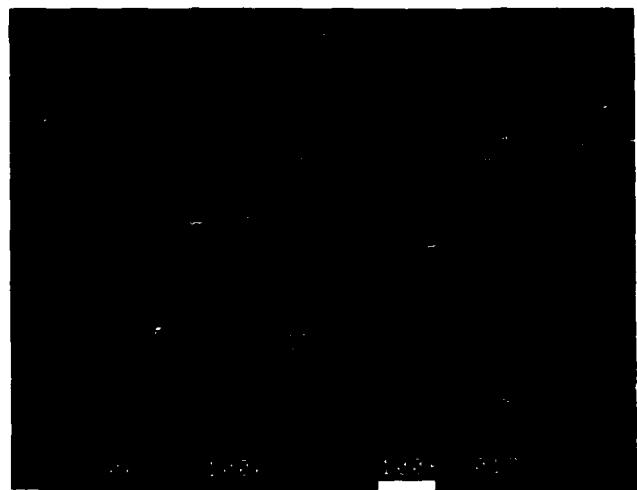
Back Scattered Image

Figure 9:  
HSSA 22, 50N. Hole in Coating in Scar.

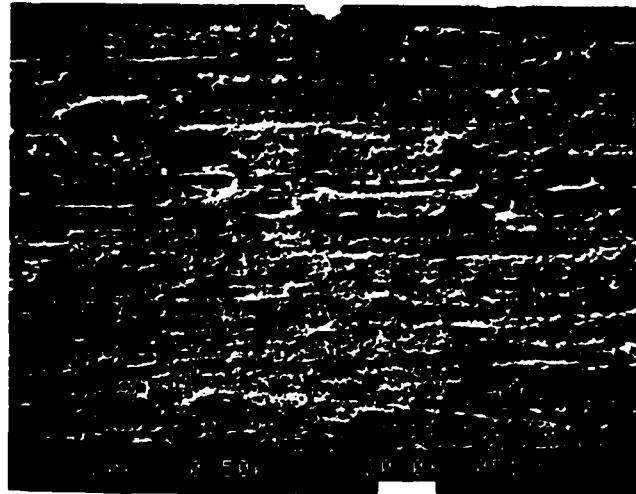
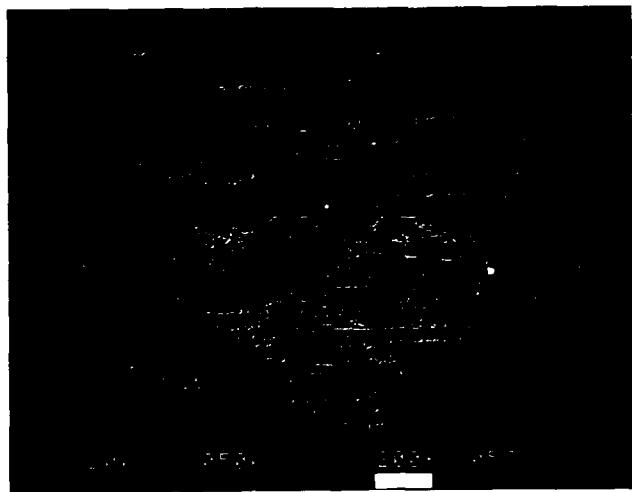
**APPENDIX 1: Scanning Electron Micrographs**



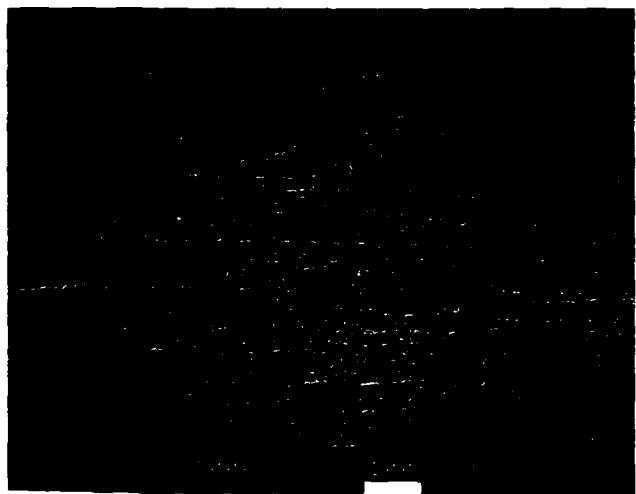
HSSA 1: Solution Heat Treated



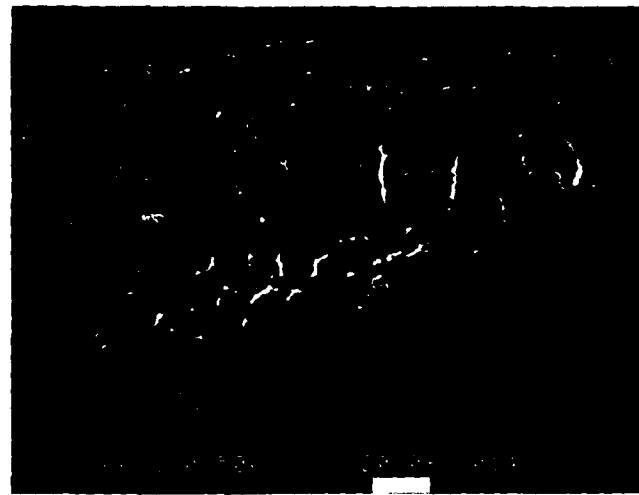
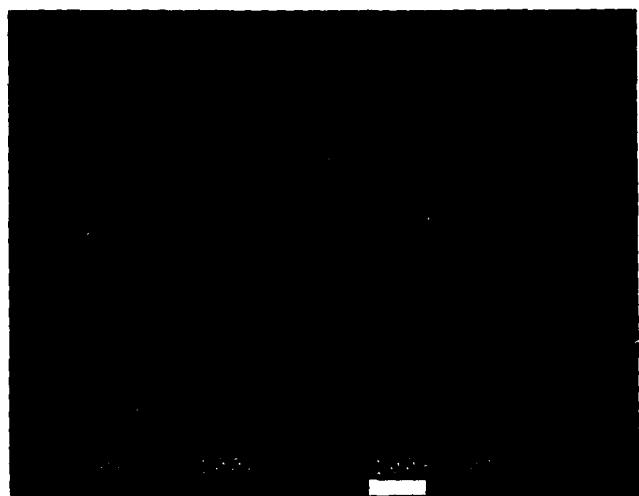
HSSA 2: Hardened and Ground



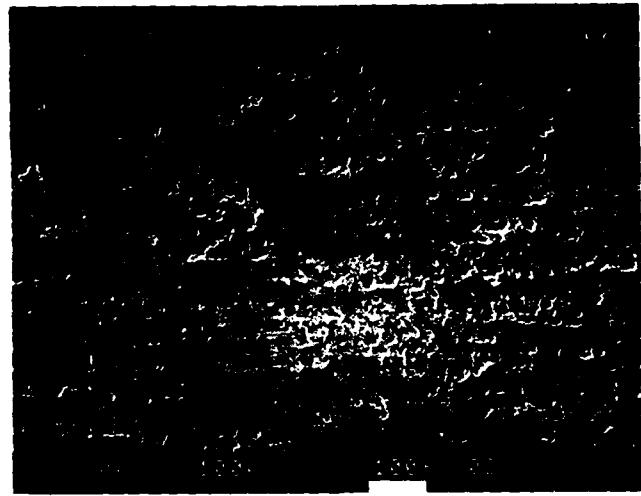
HSSA 7: Hard Anodised 1



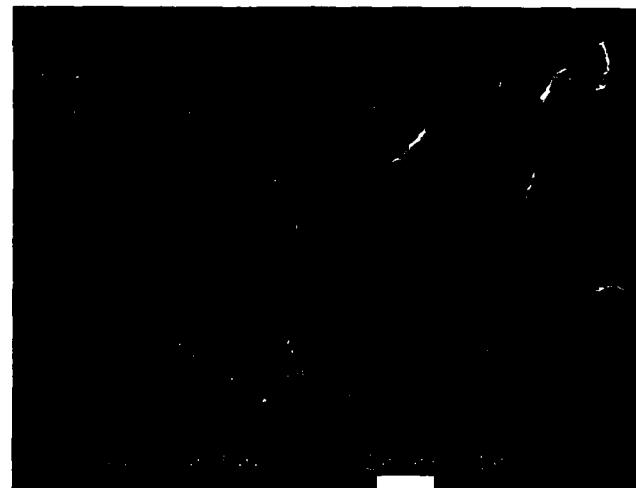
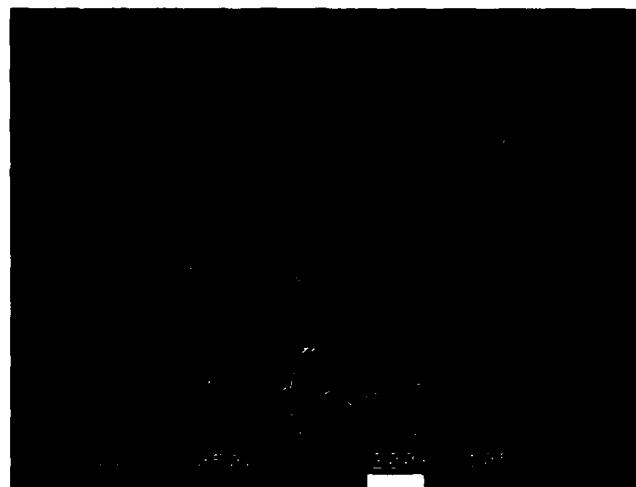
HSSA 11: Hard Anodised 4



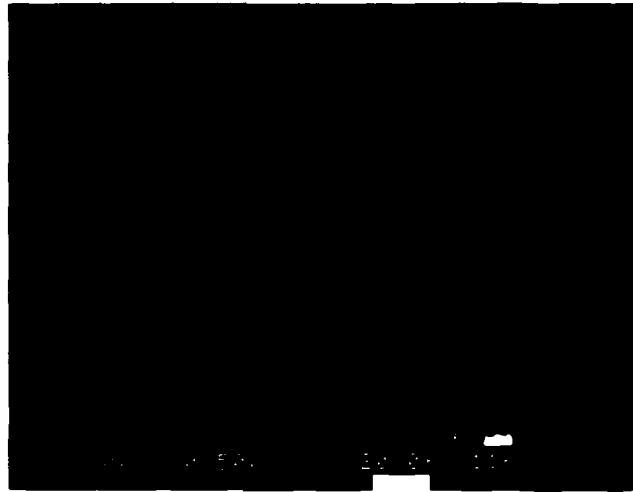
HSSA 13: Plasma Nitrided 2



HSSA 15: Nitroze 1



HSSA 19: Pack Aluminising 2



HSSA21: Diamond-like Carbon



HSSA23: TiN/HfN Multilayer

**APPENDIX 2: Optical Micrographs**

HSSA

samples  
1,2 & 3

HSSA 1

HSSA 2

HSSA 3

HSSA 4

HSSA 5

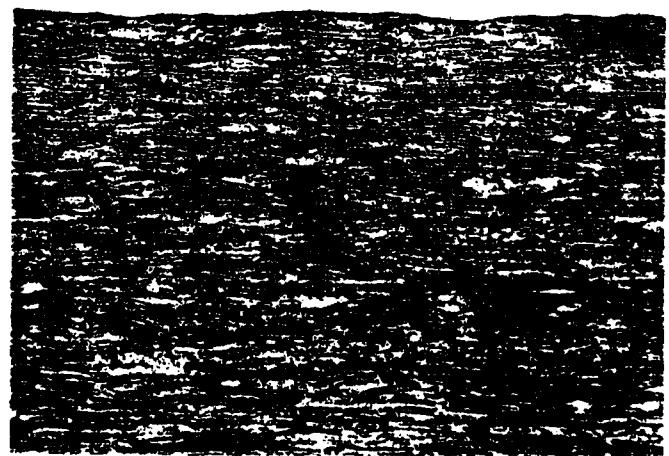
HSSA 6



6362



6363



6364

SSA  
samples  
485

HSSA 4

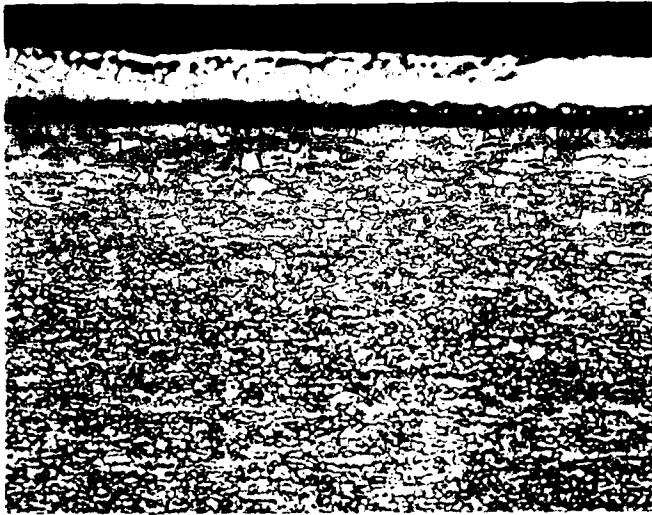
\200

HSSA 5

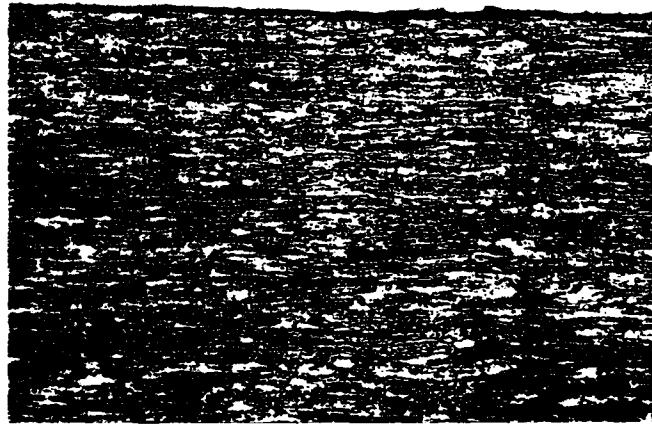
\200

HSSA 5

\1300



6365



6367

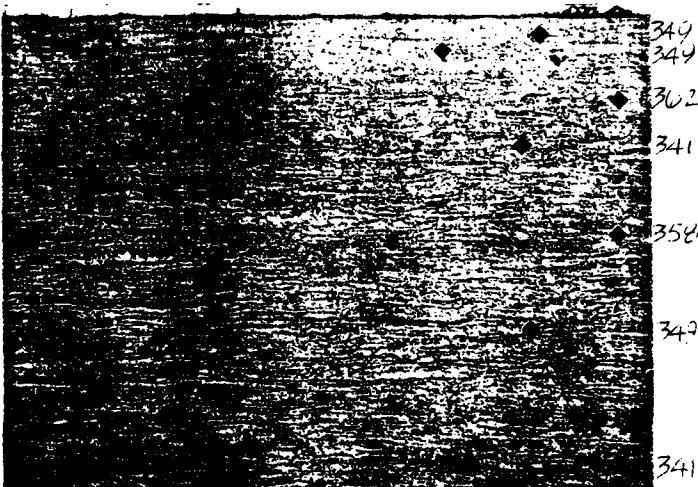
150A 6

HSSA6 side(b) X200

Hardened + Ion Implanted  
HSSA6 side(a) X200



5451



5450

bulk = 391 HV (50g)

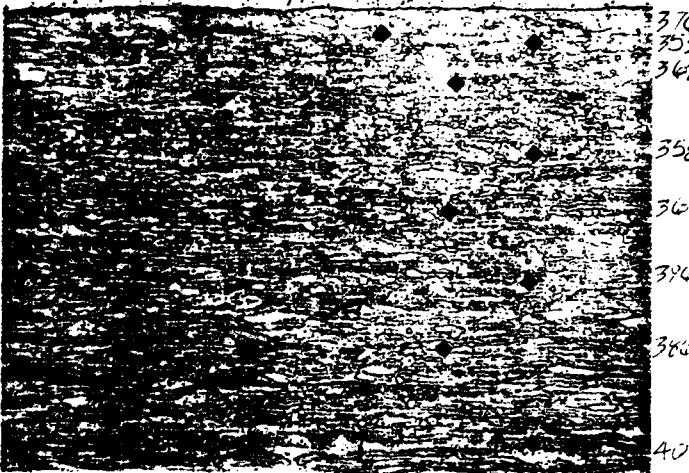
HSSA7

Sohr Treated  
HSSA7 foeton Anodized 200

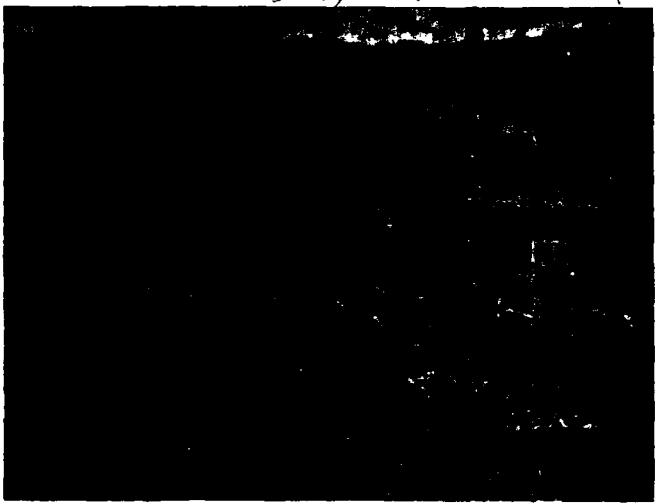
HSSA7

X1000

S.T.  
HSSA7 centre X1000



5449 bulk = 401 HV (50g)



5448



5447

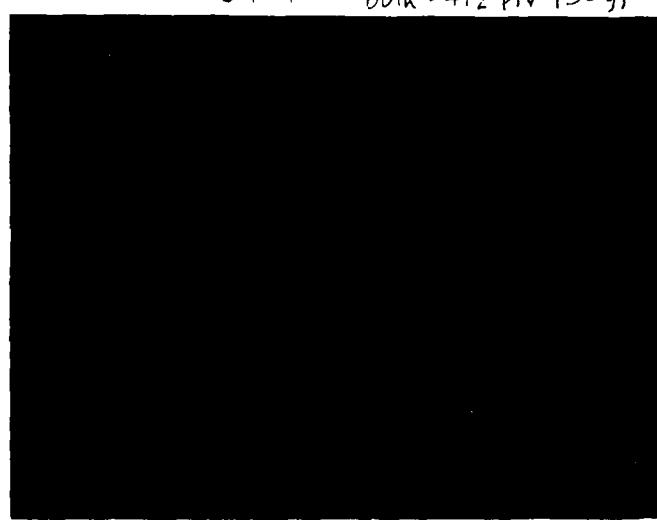
HSSA 8

HSSA 8  
Hardened  
Ground X 200  
Pecton Anodised

HSSA 8

X 1000

HSSA 8 centre  
X 1000



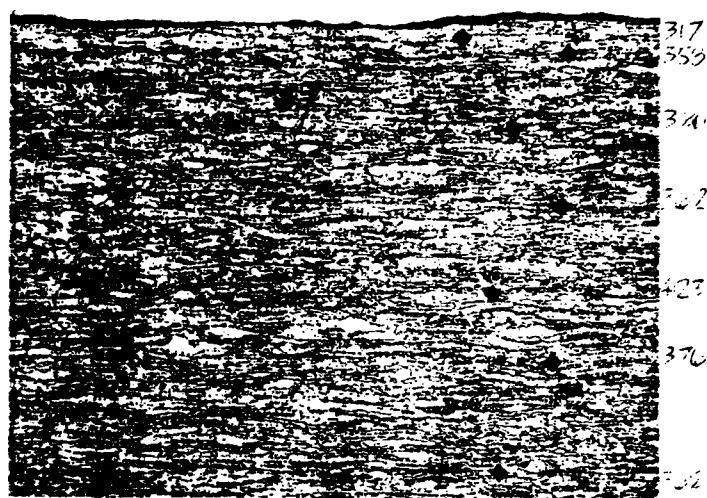
HSSA 9

HSSA 9

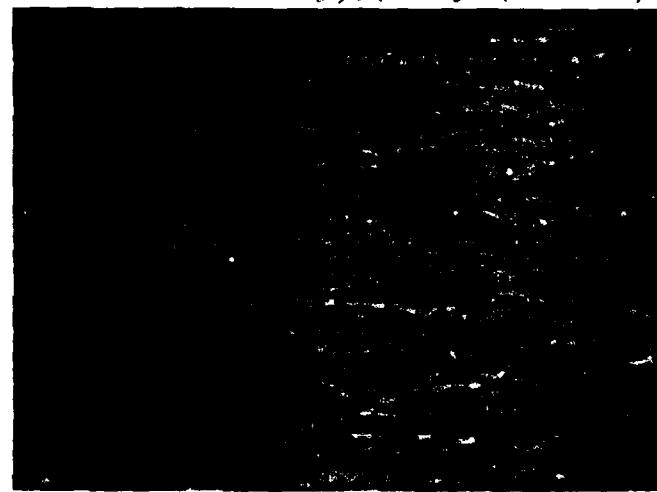
x200

HSSA 9

x1000



bath = 35911V 5459



5458

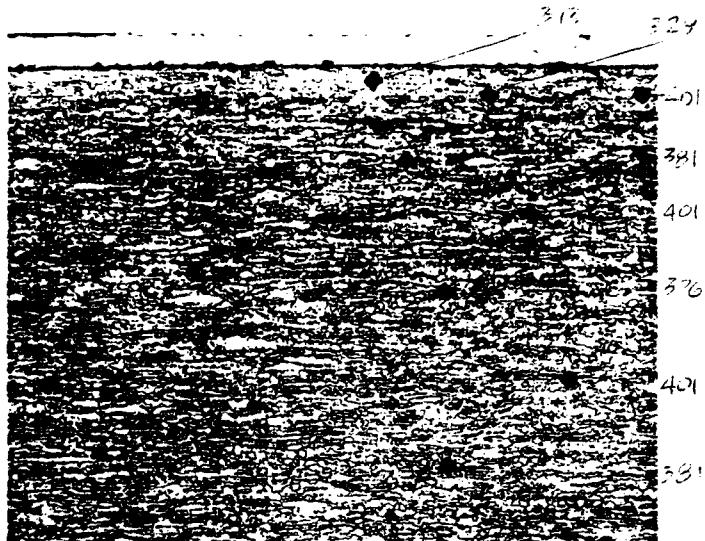
HSSA II

HSSA II

X200

HSSA II

X200



bulk = 40 THV 5453



5452

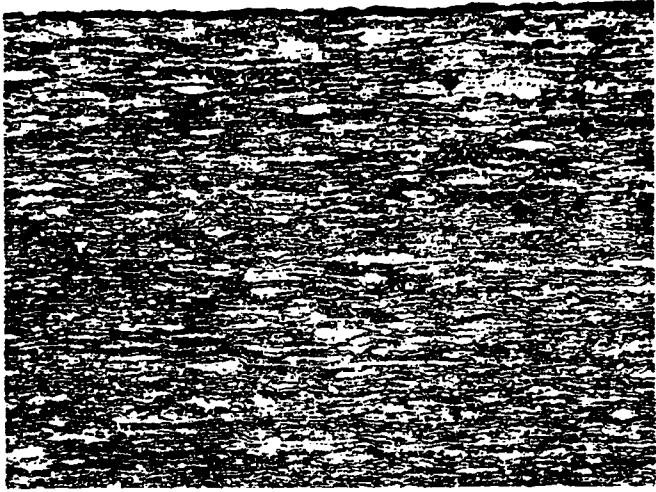
HSSA 12

HSSA 12

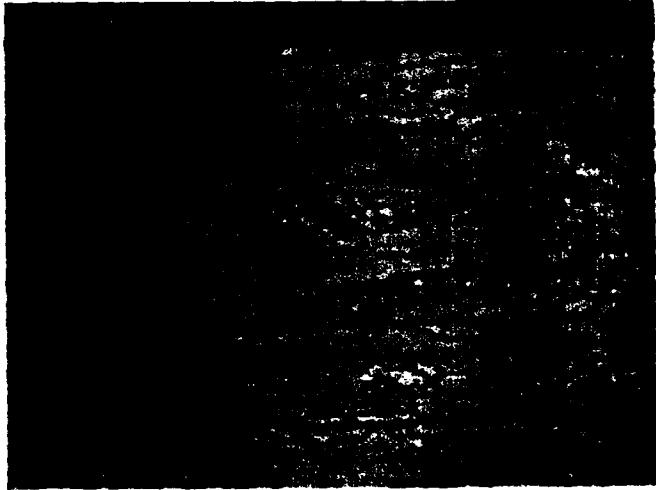
x200

HSSA 12

x1000



bulk = 1.11 g 5457



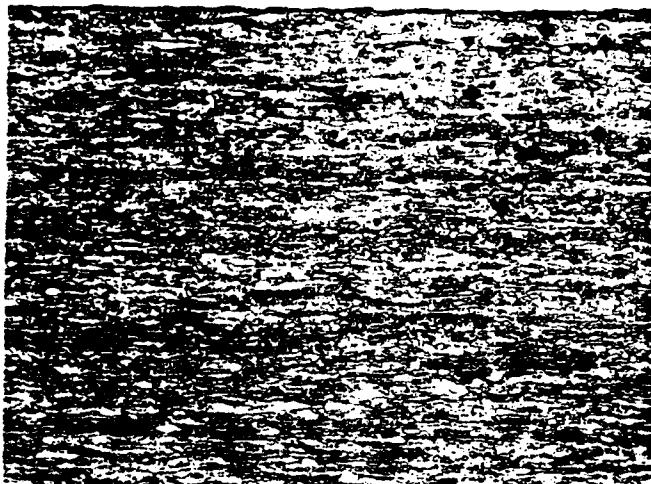
5456

HSSA 13

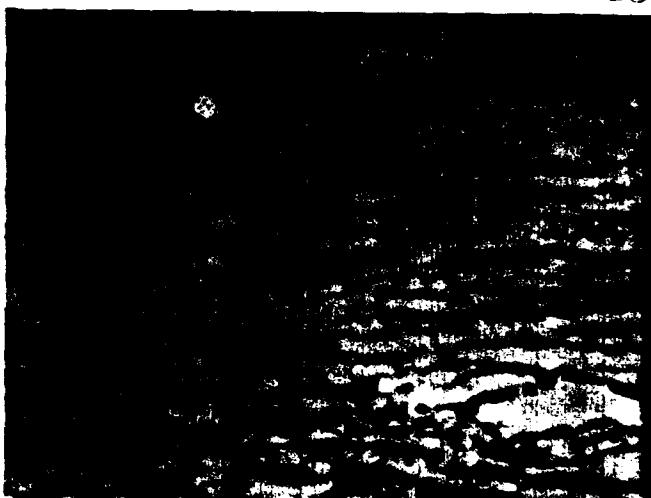
HSSA 13

x200

HSSA 13  
center x 1000



bulk = 4.07 HV 5455



5454

SSA 14

353

( $\text{Fe}_3\text{O}_4$ , 15 sec)



X200

SSA 14

SSA 15

384 396

384

( $\text{Fe}_3\text{O}_4$ , 15 sec) 5699



X200

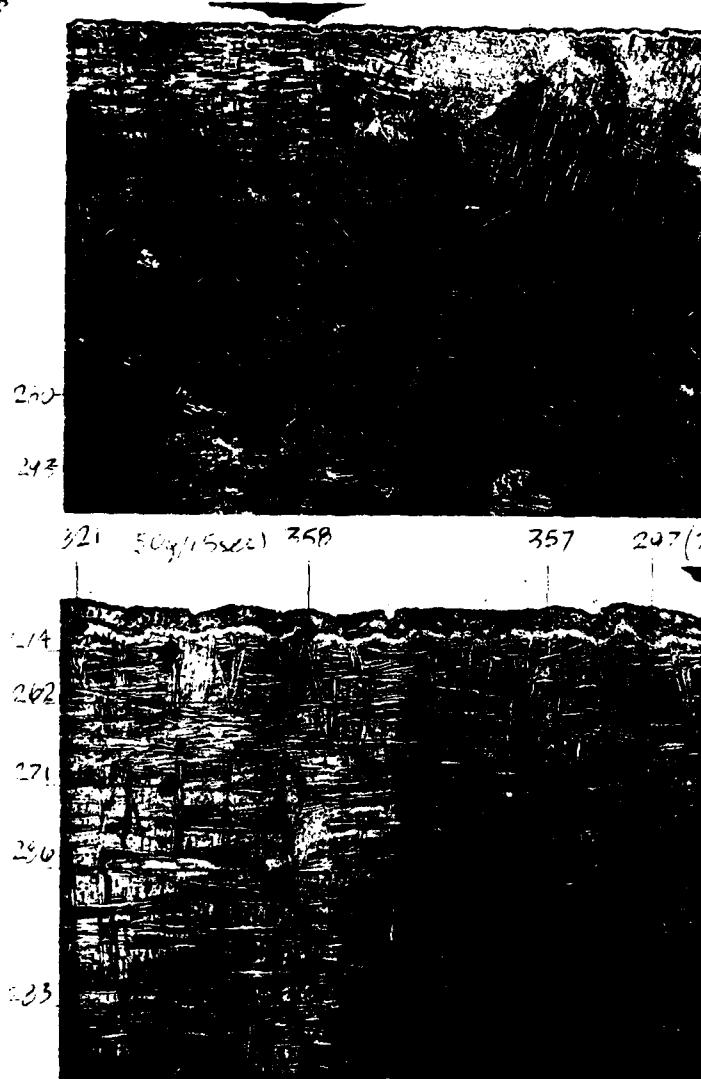
SSA 15

rnk  $\downarrow$  4011V

BULK  
MACRO (20kg) = 288HV

HSSA 16

5705



X50

HSSA 16

X200

5701

HSSA 16

$$\text{bulk} \downarrow \frac{280}{293} \text{ fHV}$$

$$\text{bulk}_{\text{bulk}} = \frac{280}{293} (\text{fHV}) = \frac{313}{371} \text{ fHV}$$

HSSA 16

HSSA 16

X1000

HSSA 16

X200

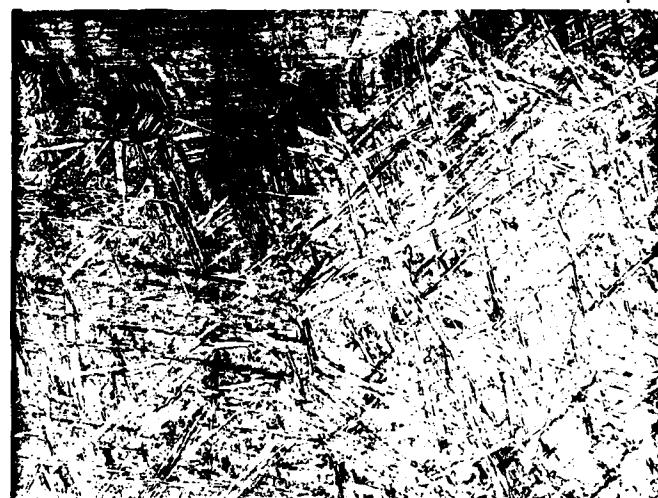
HSSA 16

X1000



5703

15μm



5704

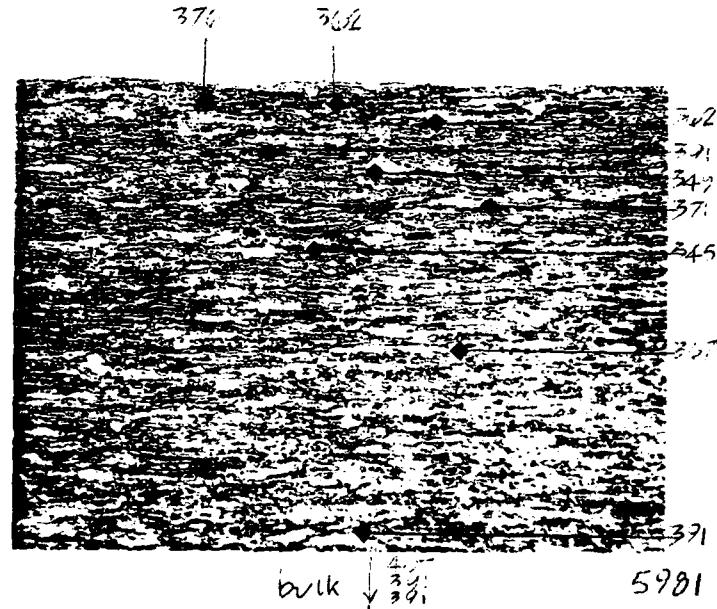
5702



HSSA17

HSSA17

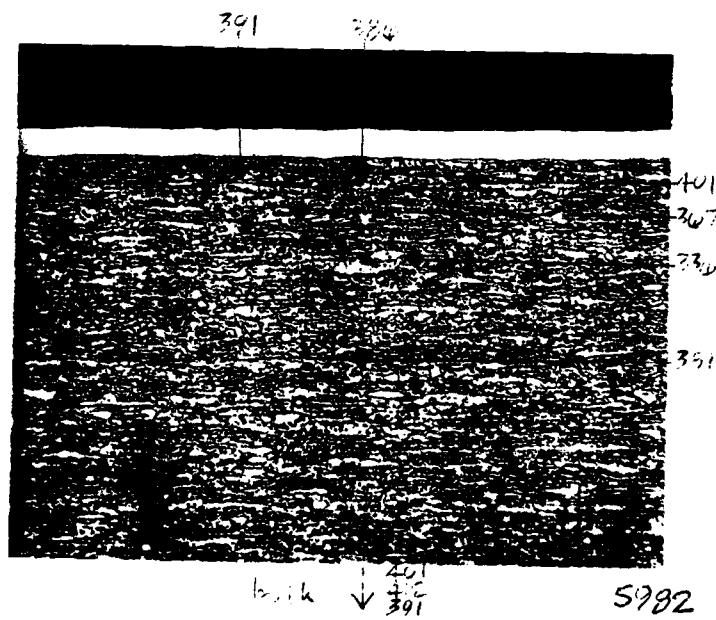
X200



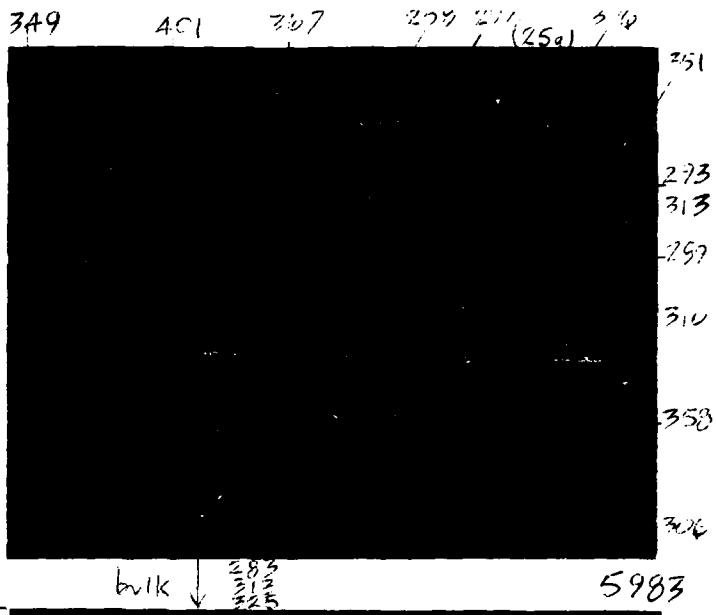
HSSA18

HSSA18

X200



HSSA 19



HSSA 19

x200

HSSA 19

x200



5984

HSSA 19

HSSA 19

x1000

HSSA 19

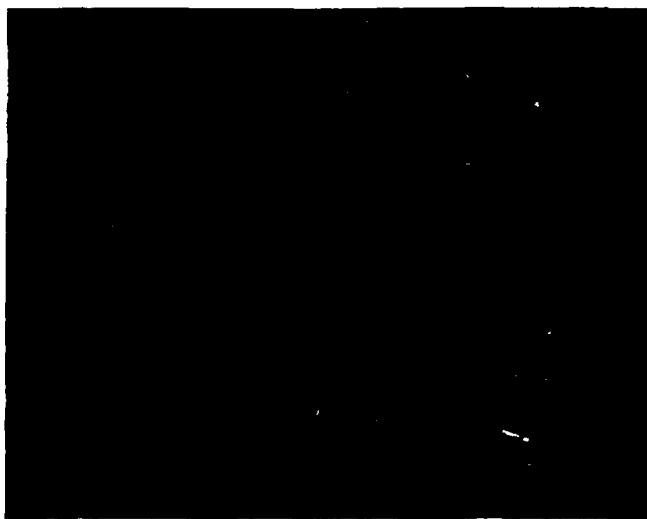
x1000

HSSA

bulk

x1000

BULK



5985



5986



5987

SSA 20

[air/Carbo  
Nitrided  
tuyton)

HSSA 20  
0  
0.1  
0.2  
0.3  
0.4  
0.5  
(mm)

100

HSSA 20

100

649 689 605

494

429

429

391

429

396

371

376

376

bulk 391  
382  
371

6062

6061

HSSA 21

Hard  
Carbon

HSSA 21

X200

371

316



↓ BULK 371

6060

1000X



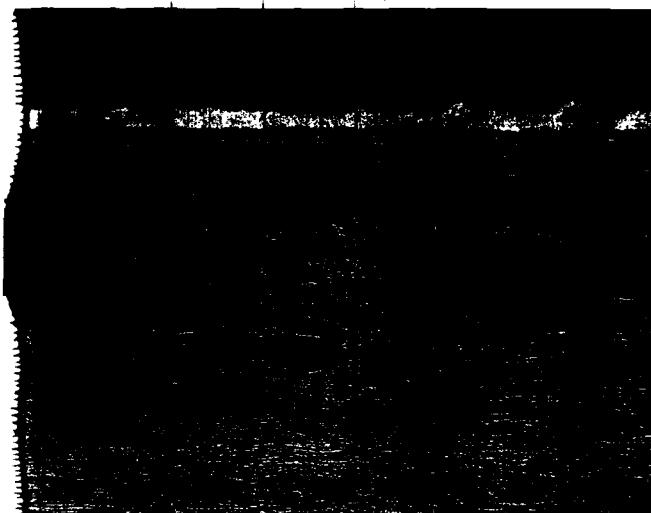
6059

1153A21

HSSA 22

'Special'  
TiN

407 41% 357



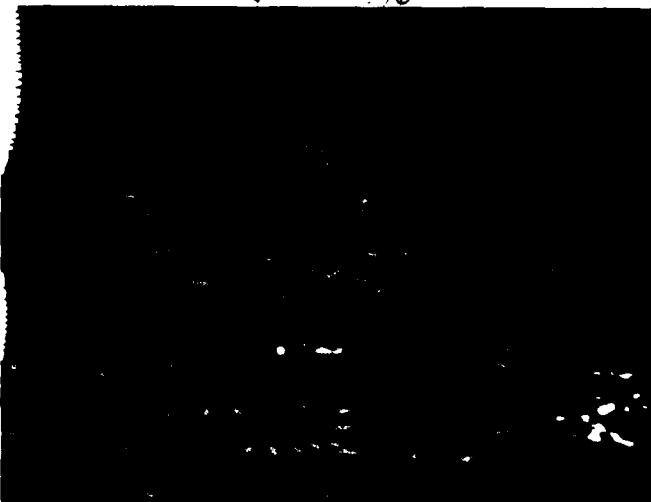
-387

HSSA 22

X200

↓ bulk 40%  
37%

6058



-388

HSSA 22

X1000

6057

HSSA 23  
TiN/HfN  
~ $1\mu\text{m}$   
layers

HSSA 23

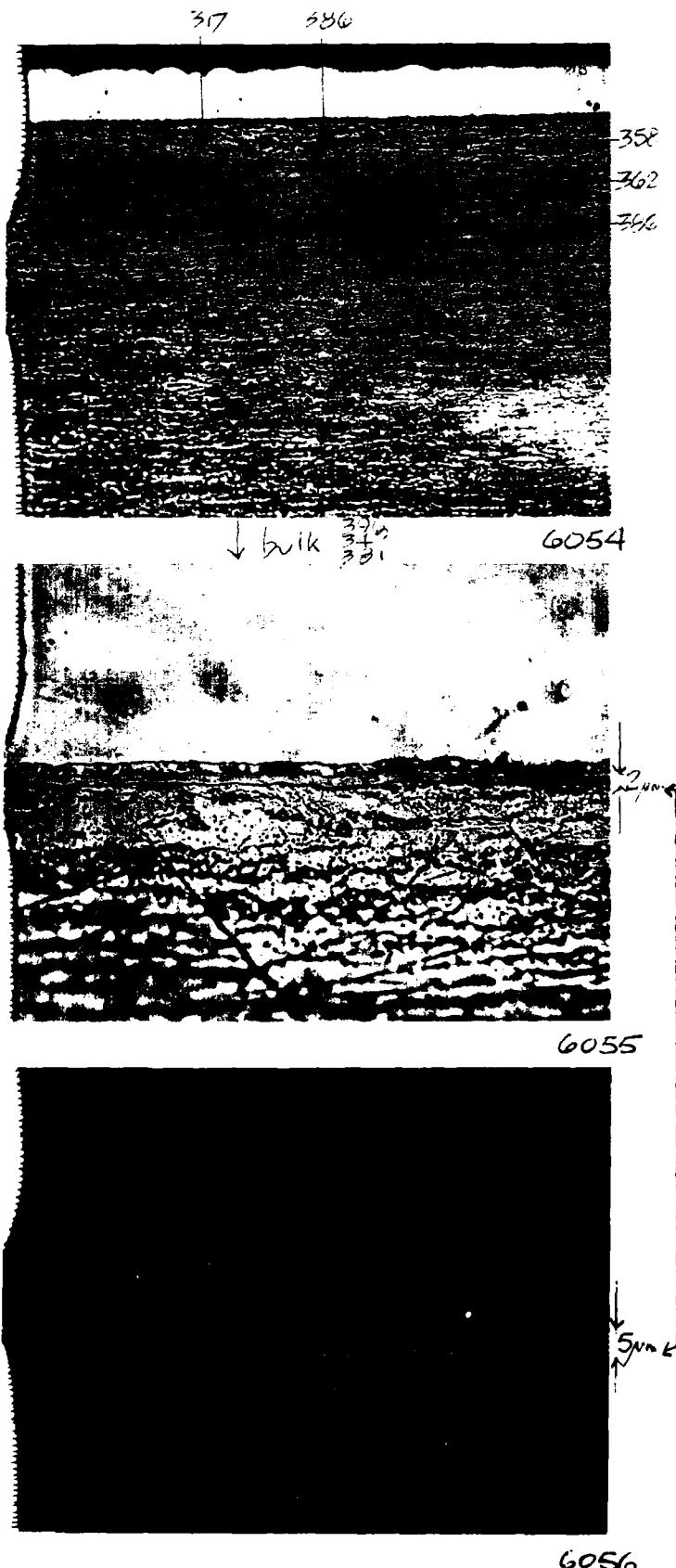
$\times 200$

HSSA 23

$\times 1000$

HSSA 23

$\times 10000$



between the 2 sides of the  
sample)

HSSA 24

Iuminised  
?AL 85

HSSA 24

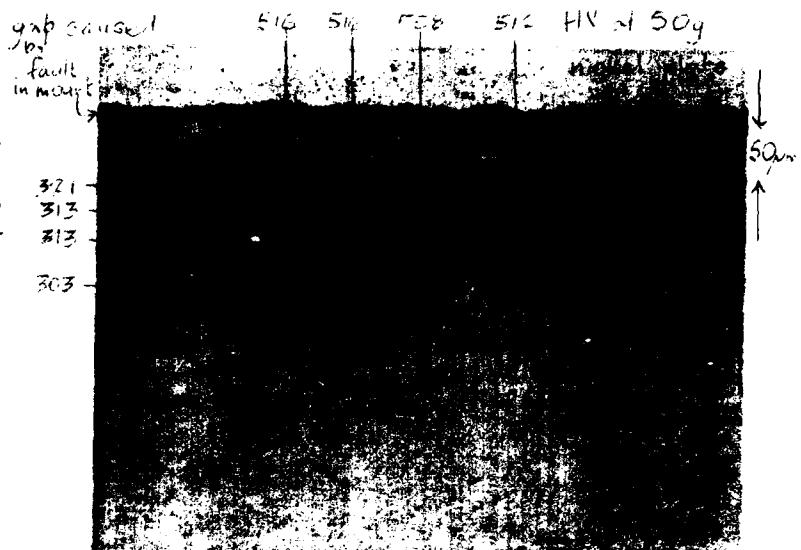
x200

HSSA 24

x200

HSSA 24

x200



G1200



G179



G178

HSSA 24

Luminised

PAL 85

HSSA 24

X1000

HSSA 24

X1000



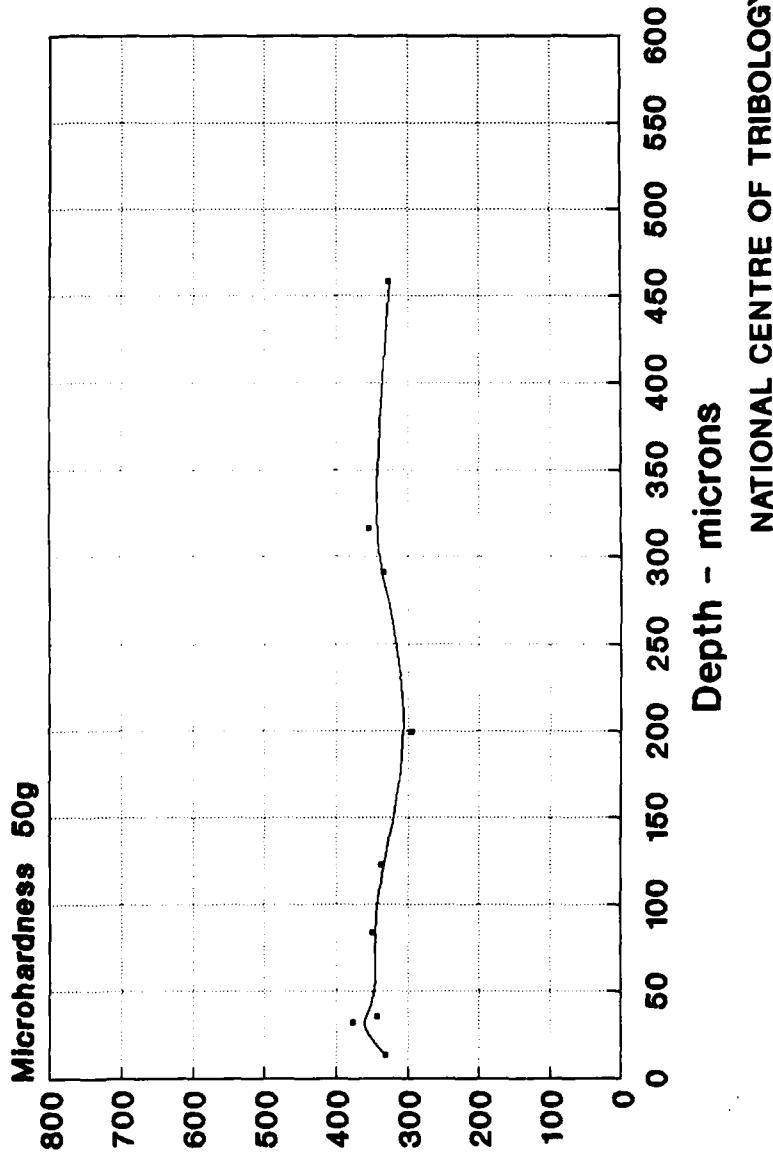
6201



6197

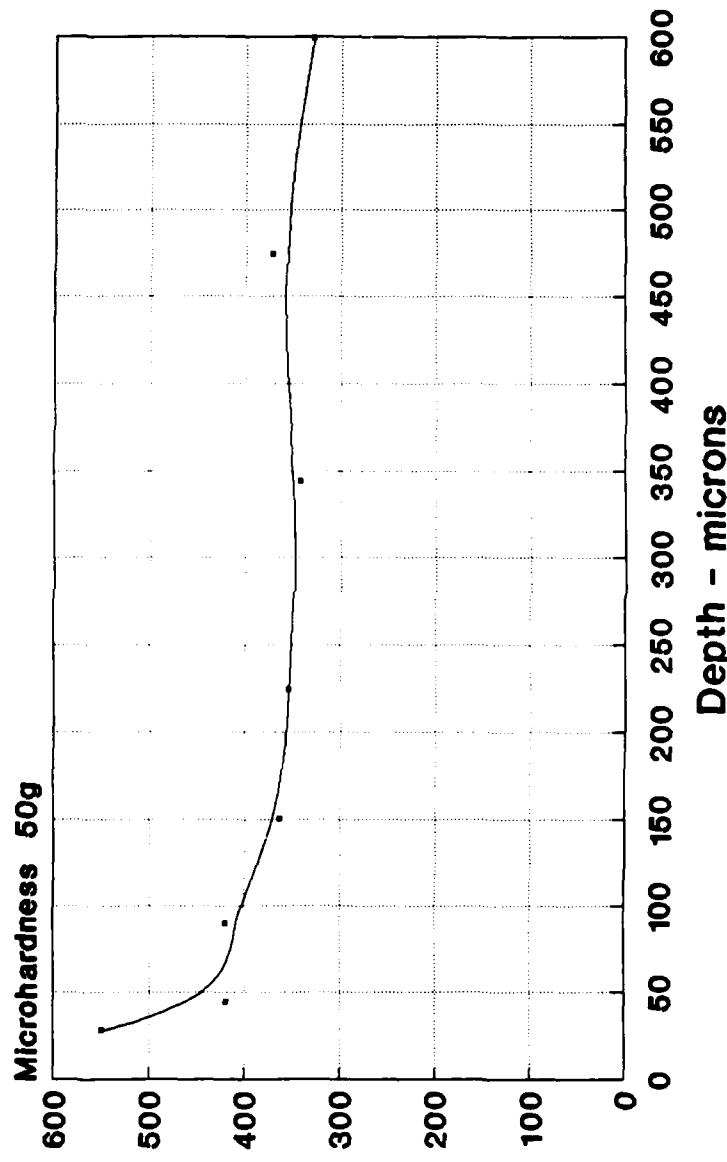
**APPENDIX 3: Microhardness Depth Profiles**

MICROHARDNESS DEPTH PROFILE  
HSSA 3 / PLASMA NITROCARBURIZED #1



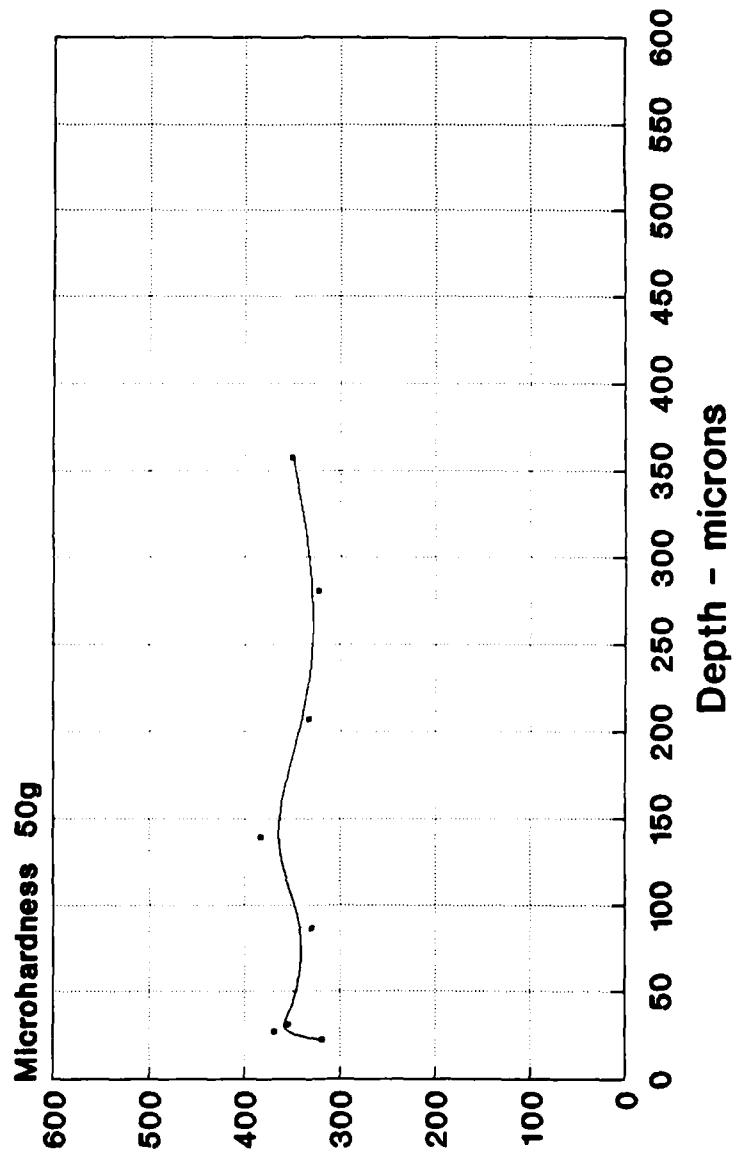
NATIONAL CENTRE OF TRIBOLOGY

**MICROHARDNESS DEPTH PROFILE  
HSSA 4 / BETA NITROCARBURIZED #1**



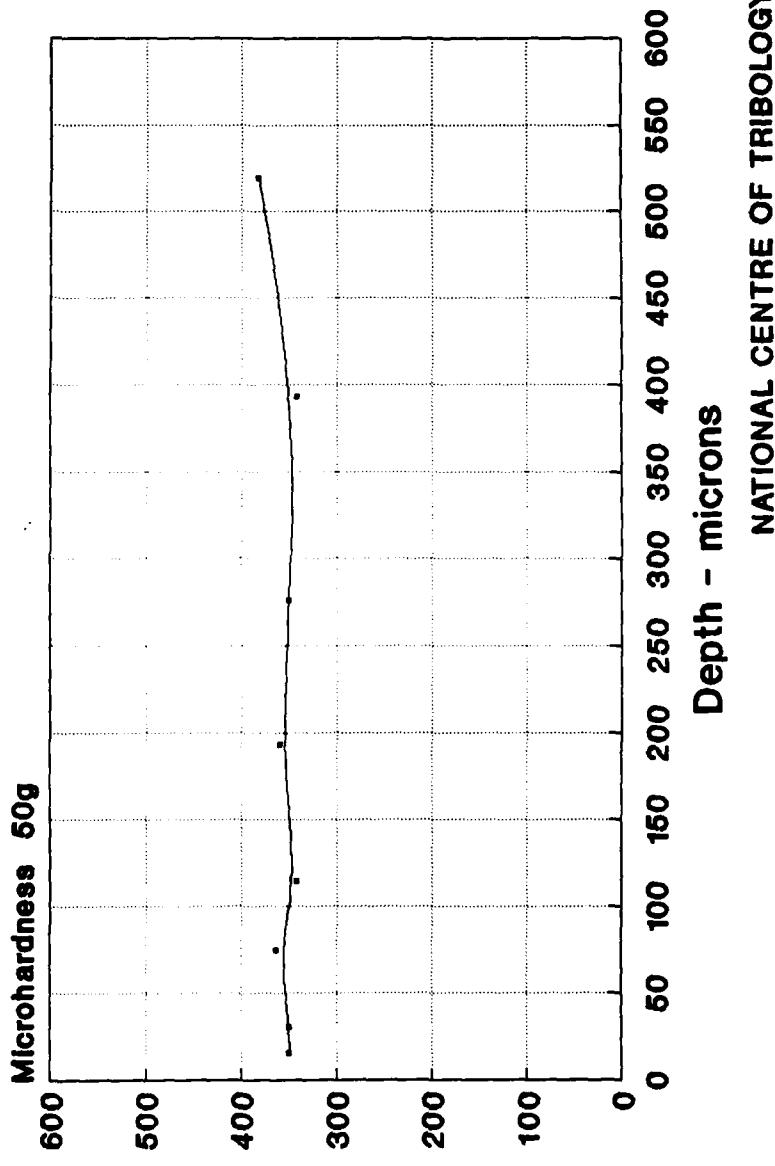
NATIONAL CENTRE OF TRIBOLOGY

MICROHARDNESS DEPTH PROFILE  
HSSA 5 / ION IMPLANTATION #1



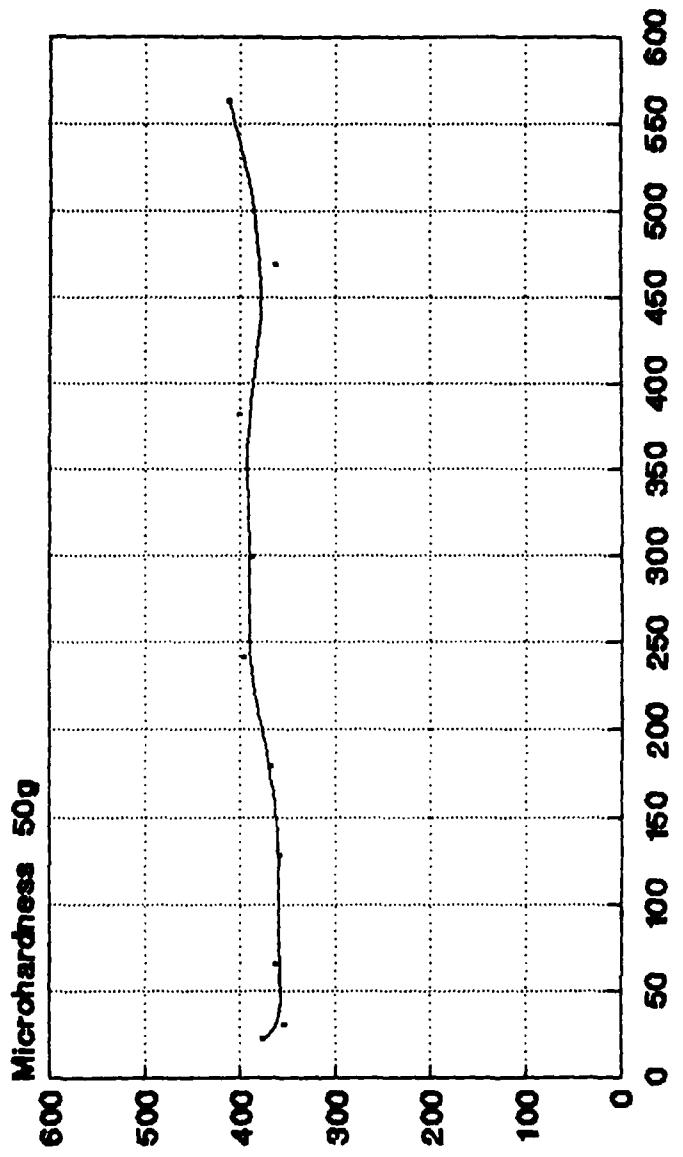
NATIONAL CENTRE OF TRIBOLOGY

**MICROHARDNESS DEPTH PROFILE  
HSSA 6 / ION IMPLANTATION #2**



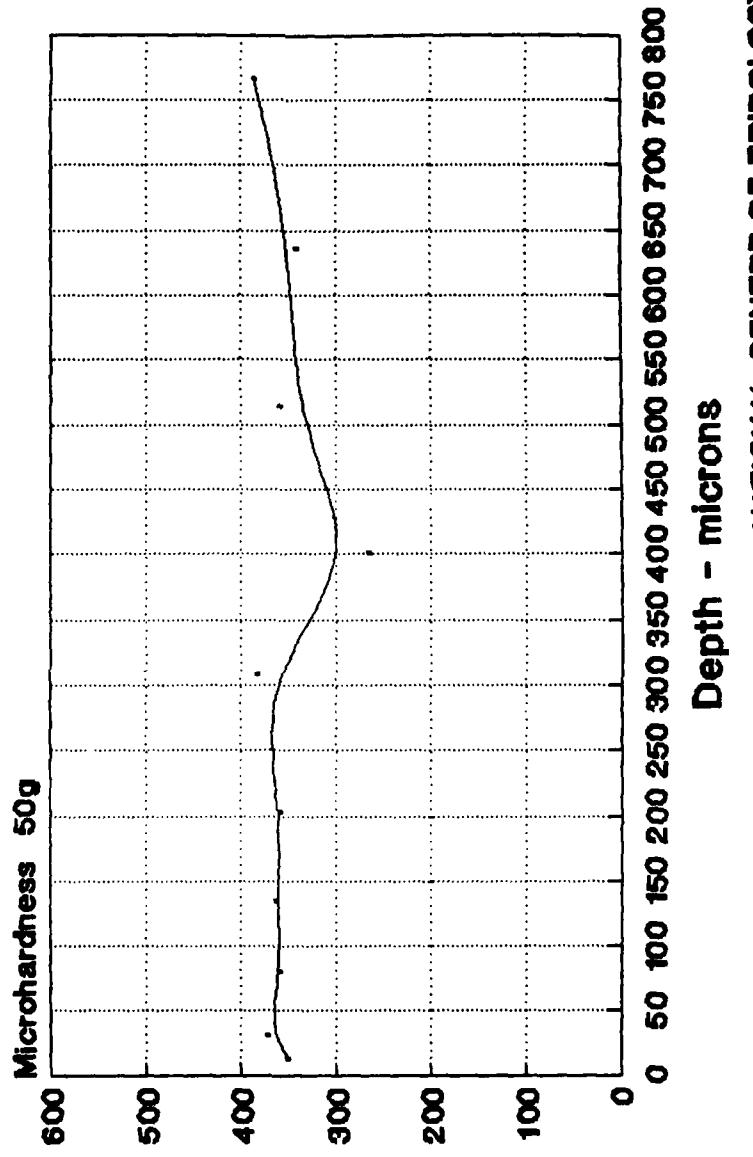
NATIONAL CENTRE OF TRIBOLOGY

MICROHARDNESS DEPTH PROFILE  
HSSA 7 / HARD ANODISED #1



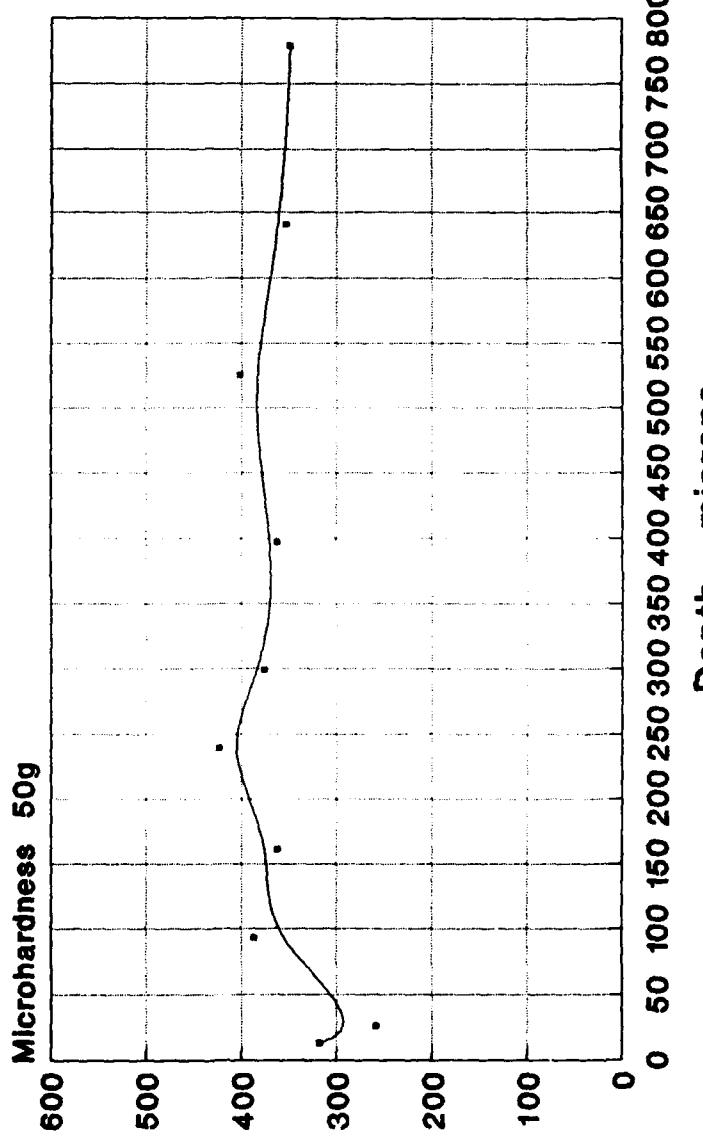
NATIONAL CENTRE OF TRIBOLOGY  
Depth - microns

MICROHARDNESS DEPTH PROFILE  
HSSA 8 / HARD ANODISED #2



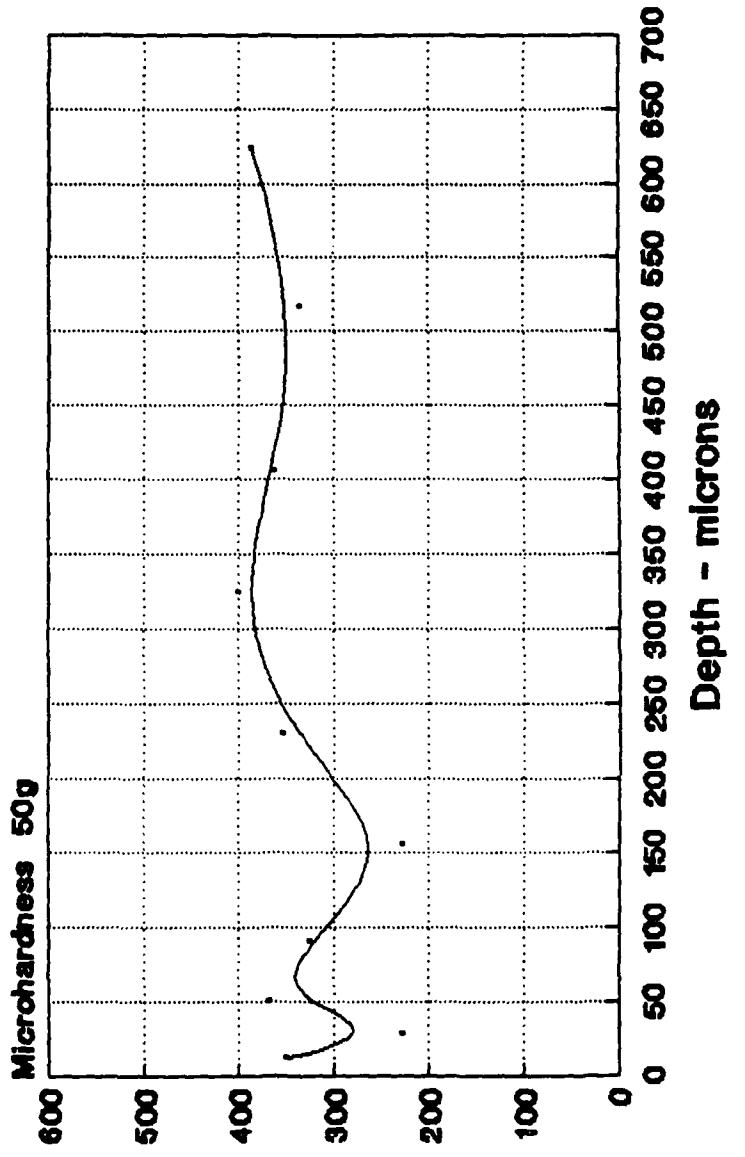
NATIONAL CENTRE OF TRIBOLOGY

MICROHARDNESS DEPTH PROFILE  
HSSA 9 / PLASMA NITROCARBURIZED #1



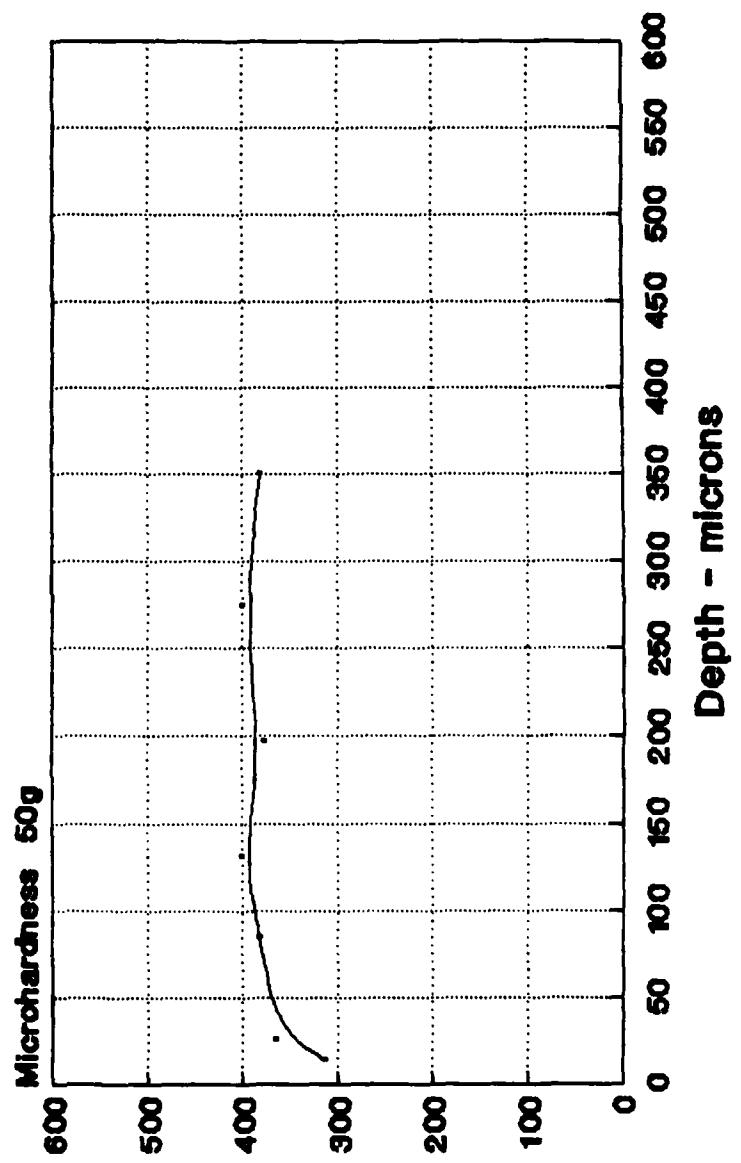
Depth - microns  
NATIONAL CENTRE OF TRIBOLOGY

MICROHARDNESS DEPTH PROFILE  
HSSA 10 / HARD ANODISED #3



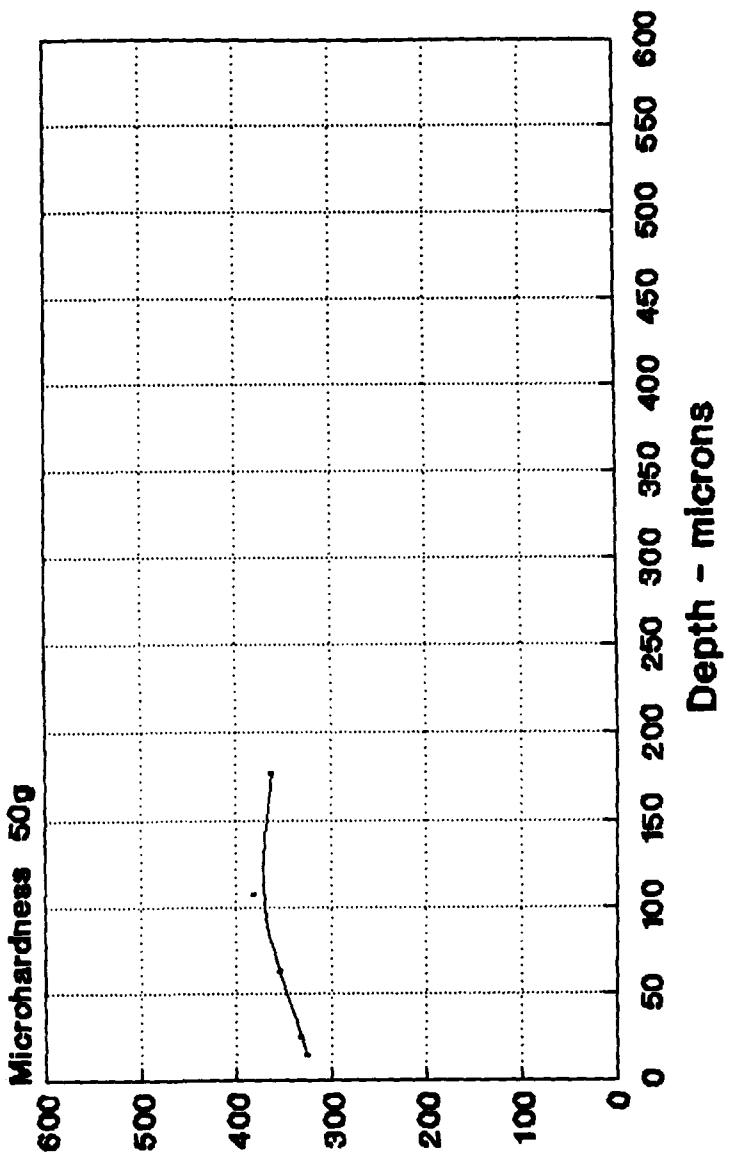
NATIONAL CENTRE OF TRIBOLOGY

MICROHARDNESS DEPTH PROFILE  
HSSA 11/ HARD ANODISED #4



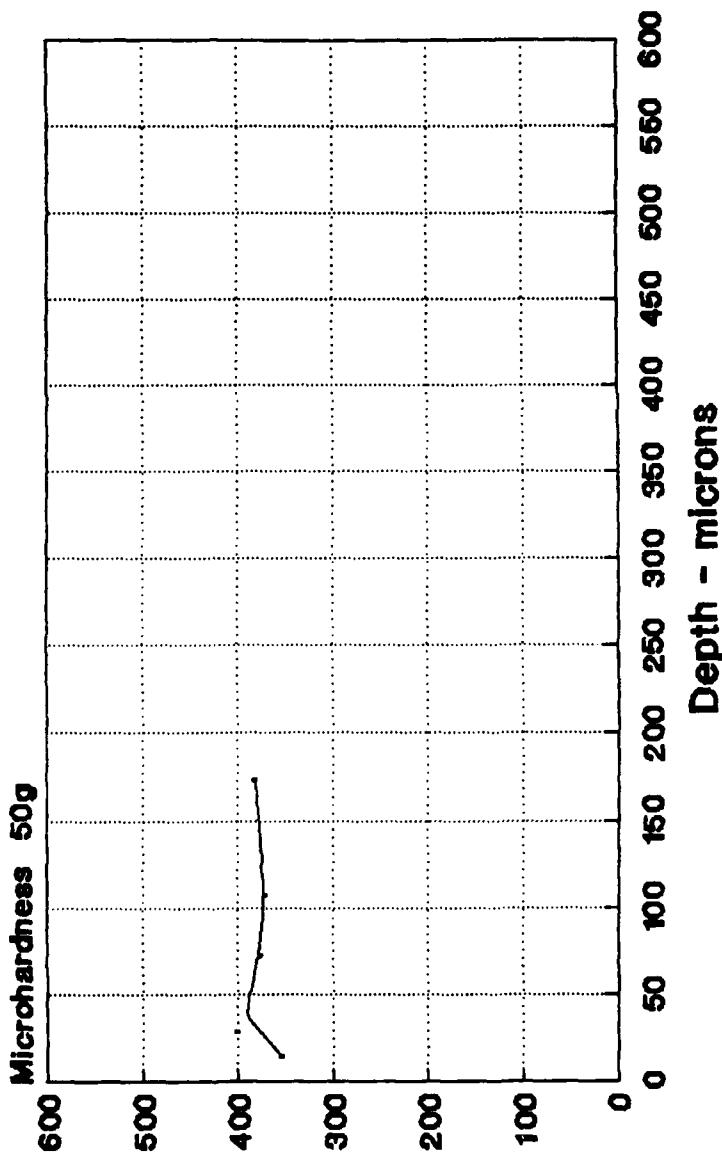
NATIONAL CENTRE OF TRIBOLOGY

MICROHARDNESS DEPTH PROFILE  
HSSA 12 / PLASMA NITRIDED #1



NATIONAL CENTRE OF TRIBOLOGY

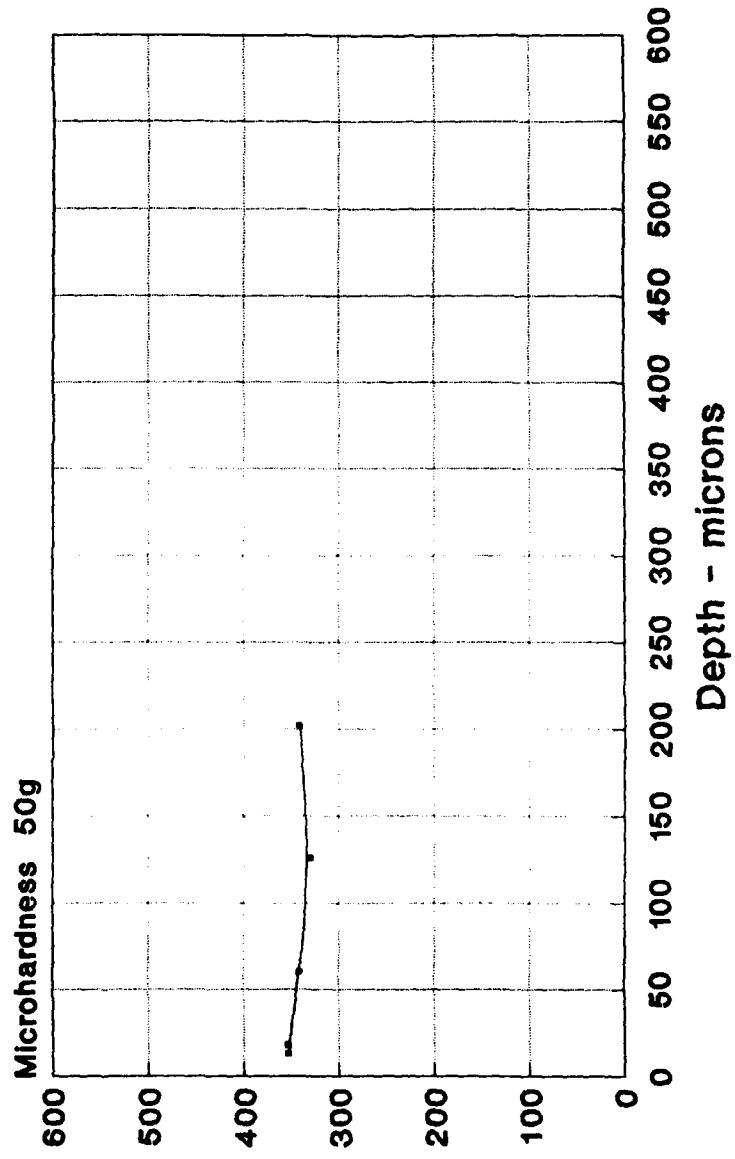
MICROHARDNESS DEPTH PROFILE  
HSSA 13 / PLASMA NITRIDED #2



NATIONAL CENTRE OF TRIBOLOGY

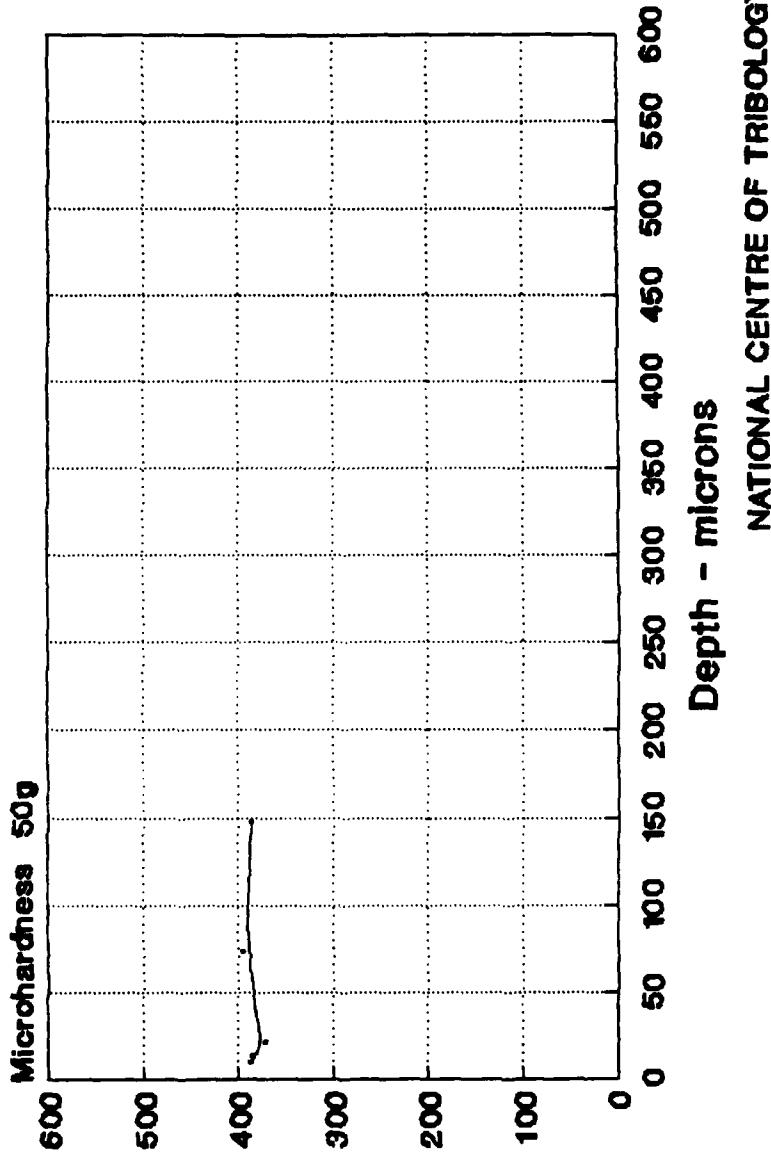
Depth - microns

MICROHARDNESS DEPTH PROFILE  
HSSA 14 / HT NITROCARBURIZING #1



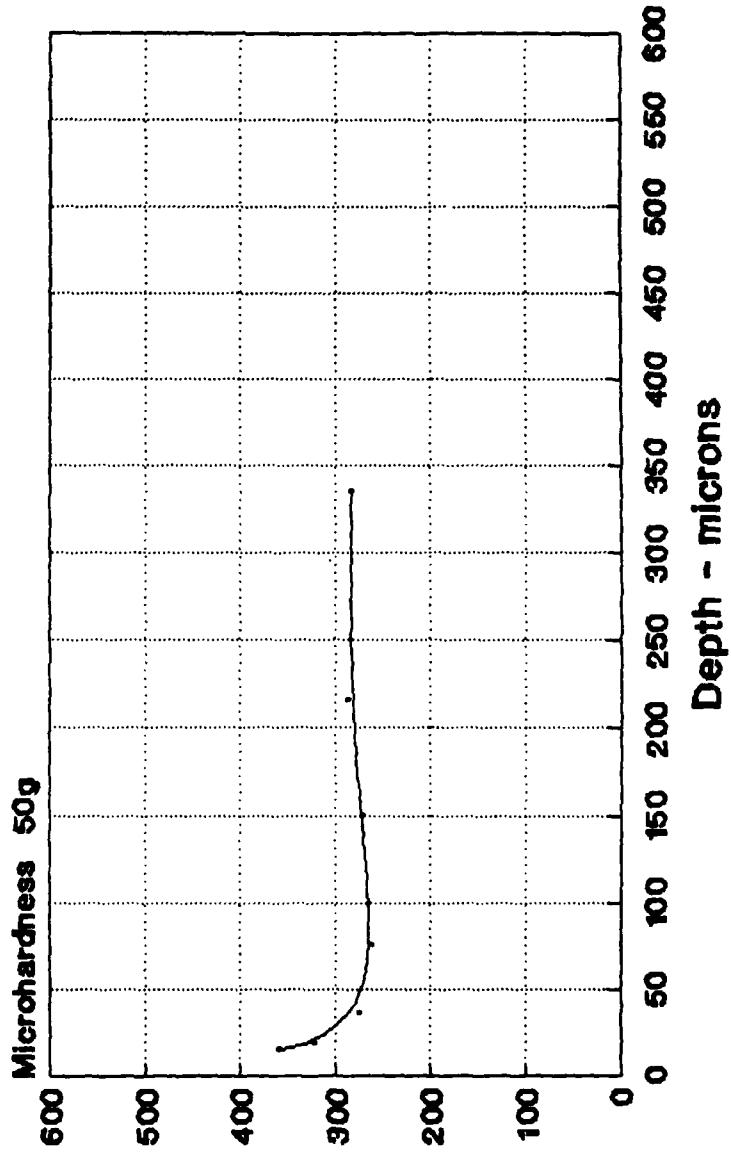
NATIONAL CENTRE OF TRIBOLOGY

**MICROHARDNESS DEPTH PROFILE**  
**HSSA 15/ NITROX #1**



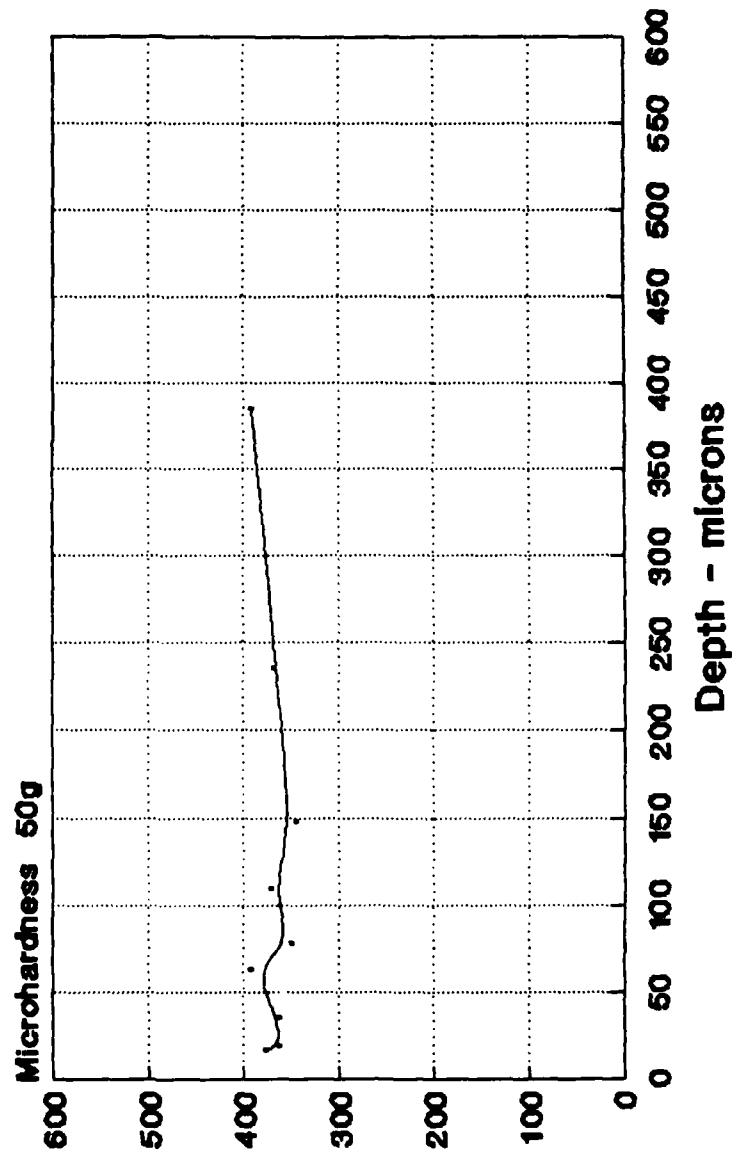
NATIONAL CENTRE OF TRIBOLOGY

**MICROHARDNESS DEPTH PROFILE  
HSSA 16 / PACK ALUMINISING #1**



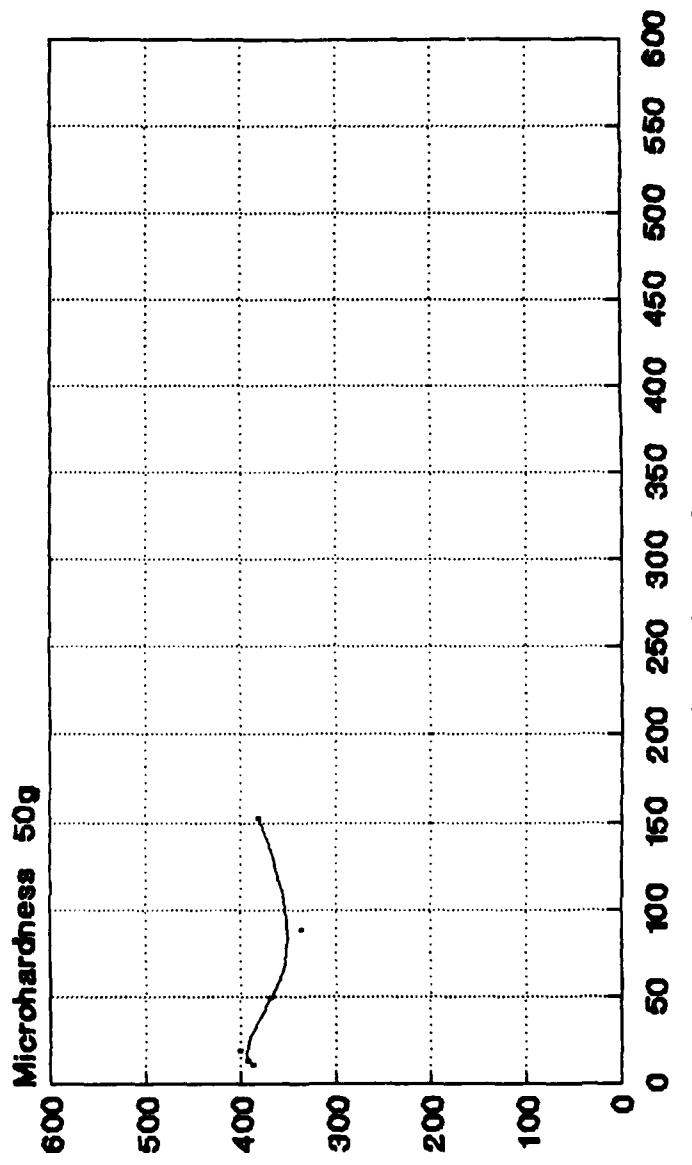
NATIONAL CENTRE OF TRIBOLOGY

MICROHARDNESS DEPTH PROFILE  
HSSA 17 / NITROX #2



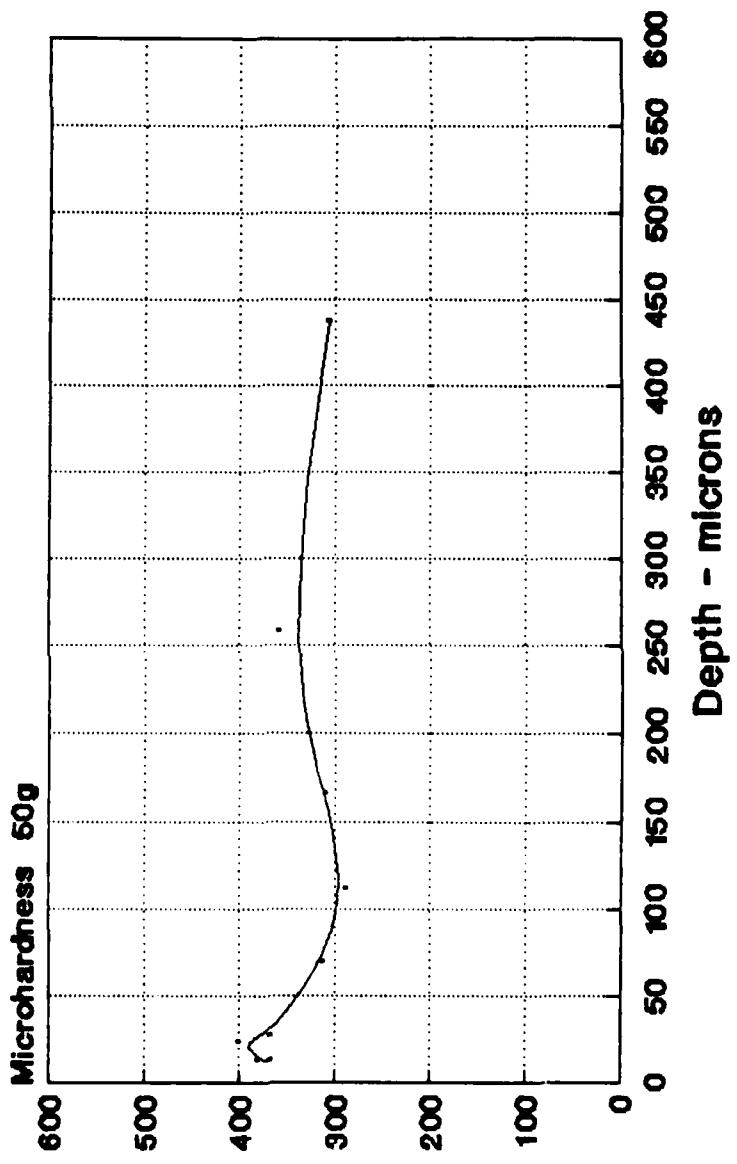
NATIONAL CENTRE OF TRIBOLOGY

MICROHARDNESS DEPTH PROFILE  
HSSA 18 / NITROX #3



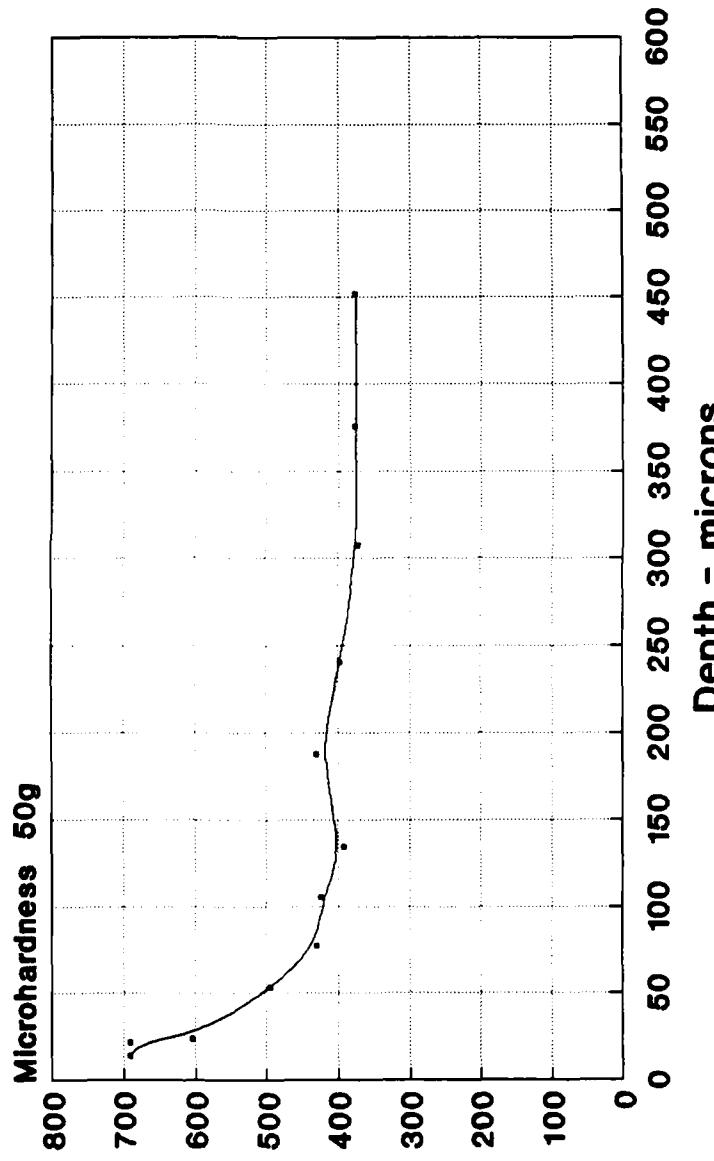
NATIONAL CENTRE OF TRIBOLOGY  
Depth - microns

MICROHARDNESS DEPTH PROFILE  
HSSA 19/PACK ALUMINISING #2



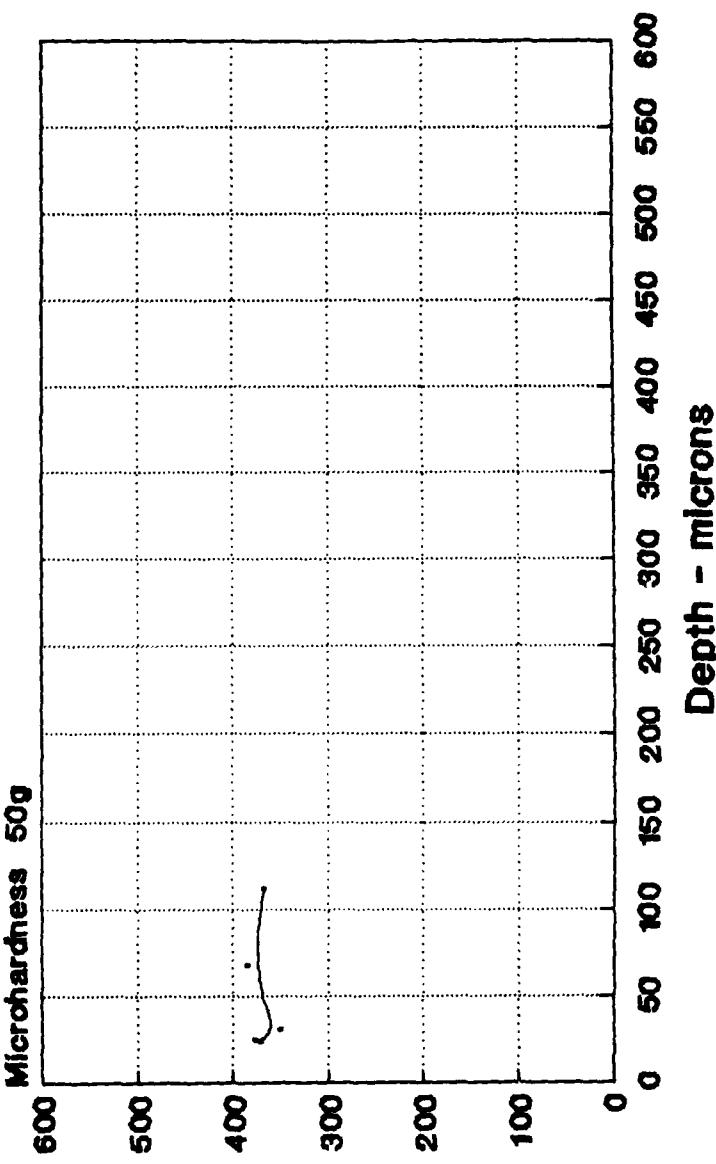
NATIONAL CENTRE OF TRIBOLOGY

MICROHARDNESS DEPTH PROFILE  
HSSA 20 / CARBONITRIDED #1



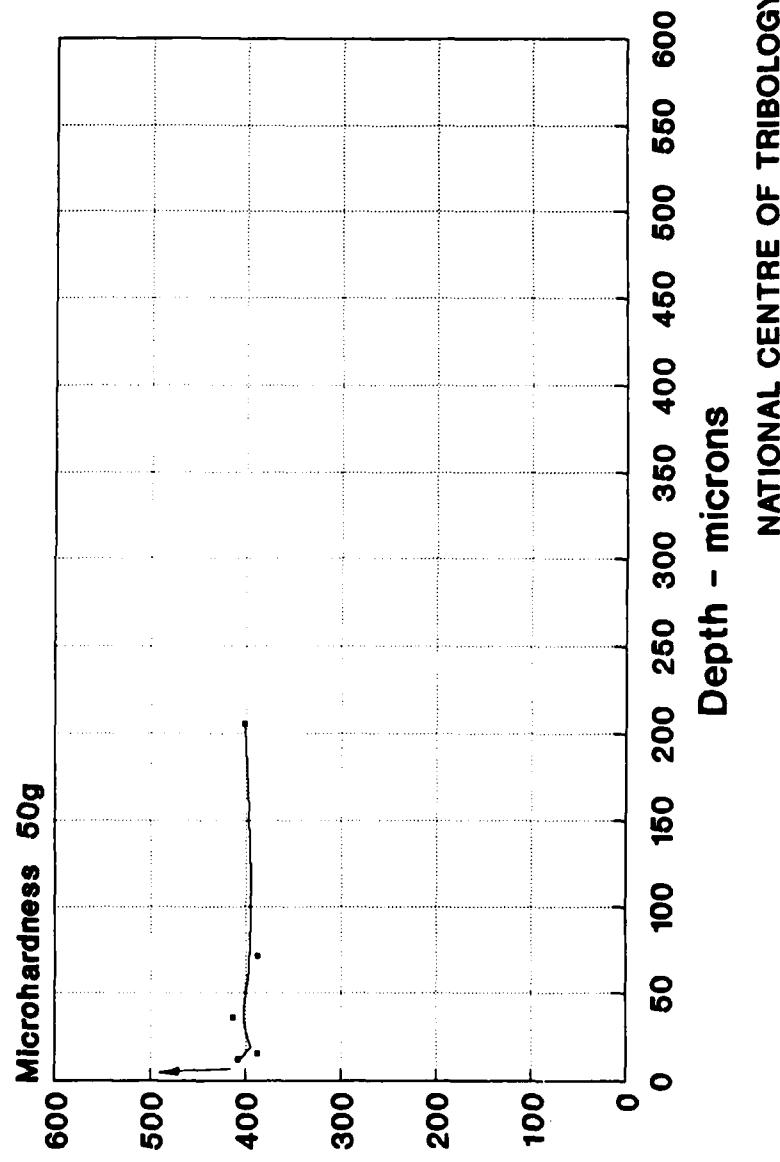
NATIONAL CENTRE OF TRIBOLOGY

MICROHARDNESS DEPTH PROFILE  
HSSA 21/ DLC #1



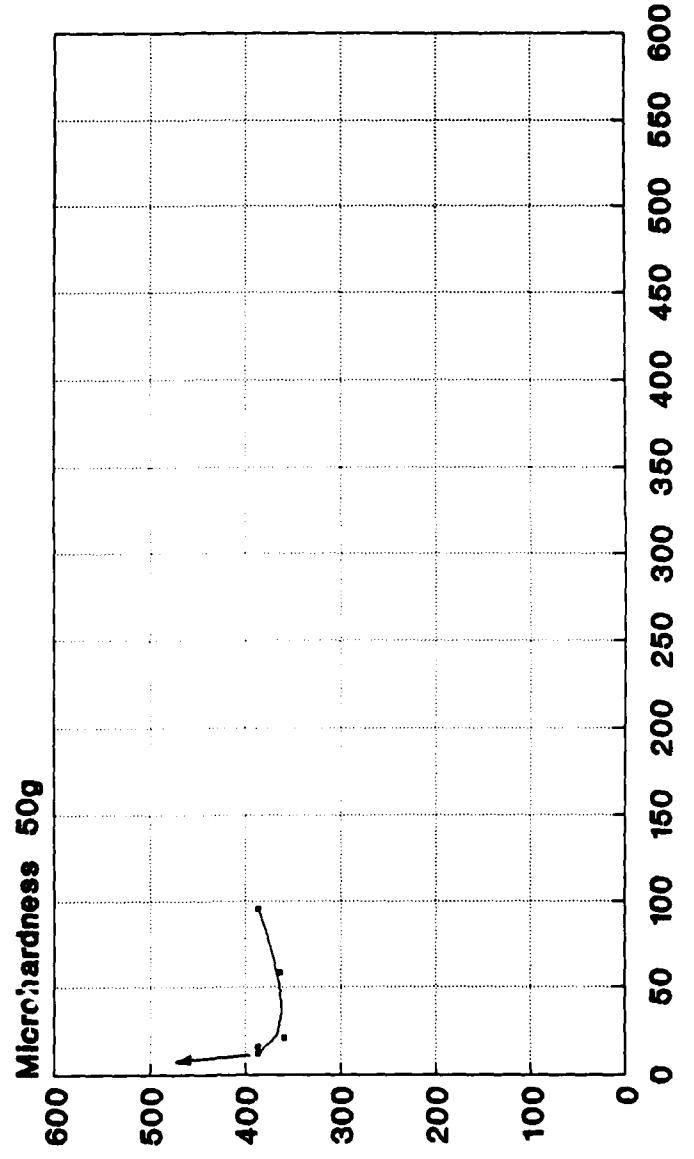
NATIONAL CENTRE OF TRIBOLOGY

MICROHARDNESS DEPTH PROFILE  
HSSA 22/TiN #3



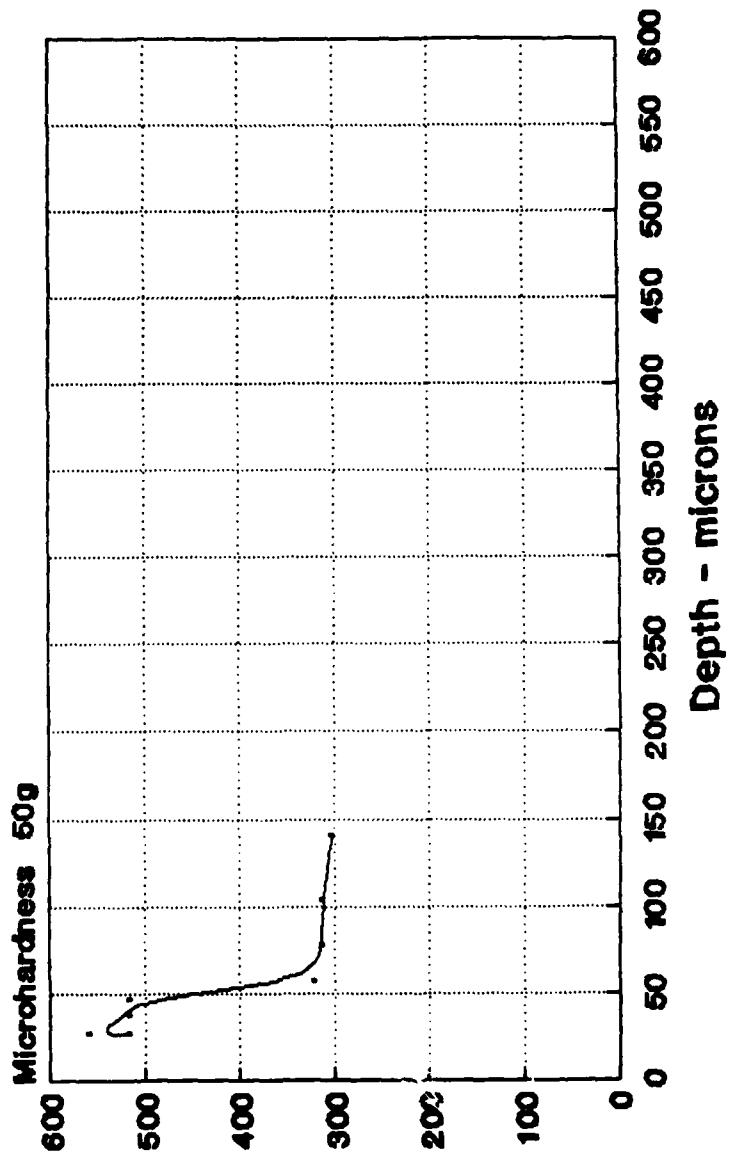
NATIONAL CENTRE OF TRIBOLOGY

MICROHARDNESS DEPTH PROFILE  
HSSA 23/ TiN/HfN MULTILAYER #1



NATIONAL CENTRE OF TRIBOLOGY  
Depth - microns

MICROHARDNESS DEPTH PROFILE  
HSSA 24 / PACK ALUMINISING #3

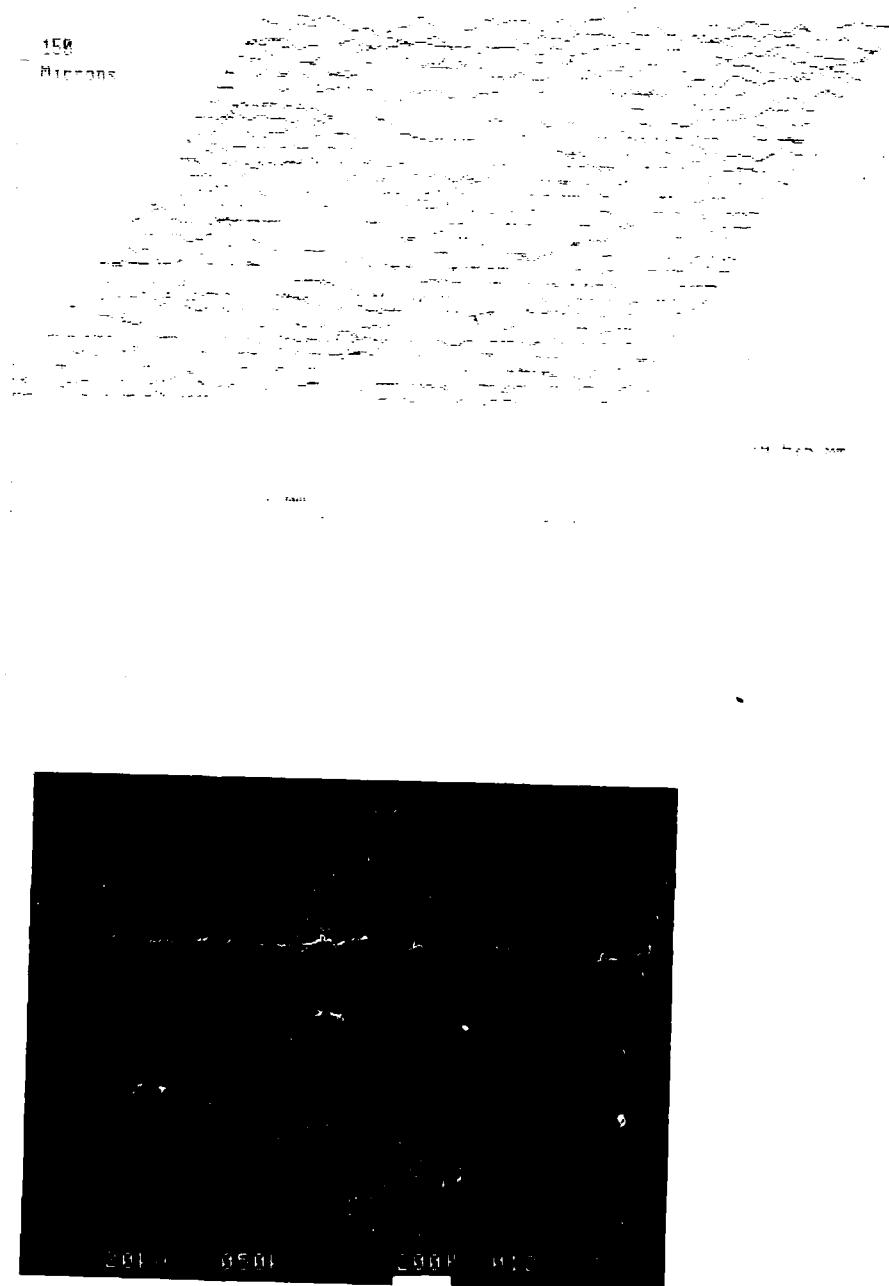


NATIONAL CENTRE OF TRIBOLOGY

**APPENDIX 4: 20N Wear Profiles and SEM Micrographs of Wear Tracks**

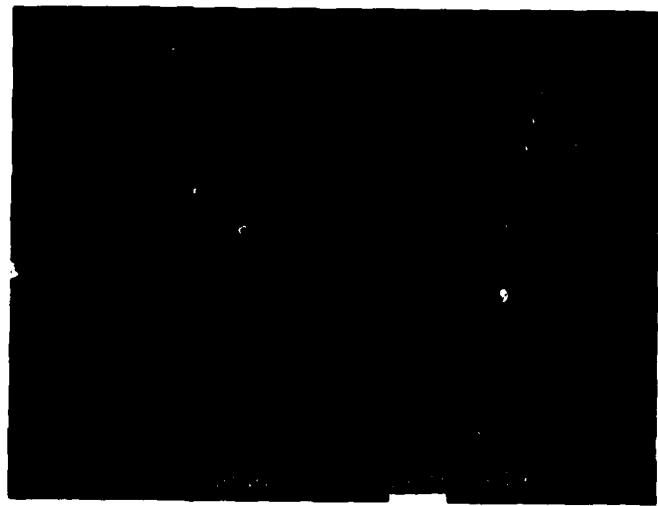
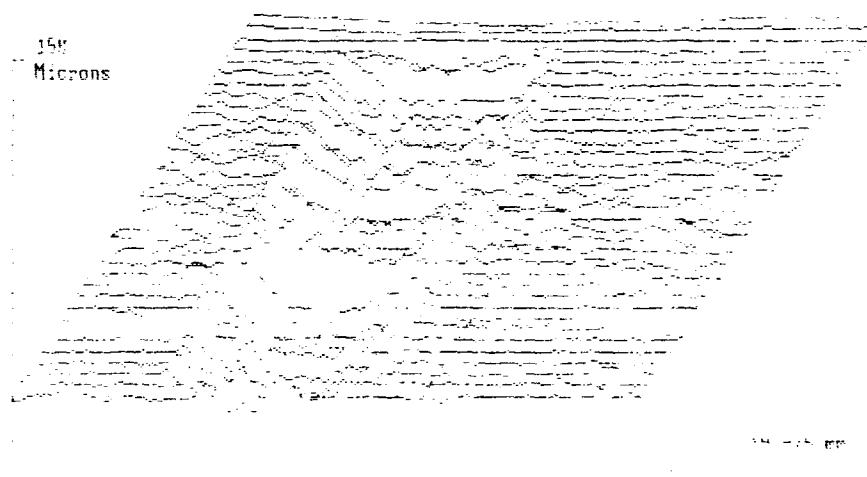
## HSSA 1: Solution Heat Treated

Data from [Waze-ia.htm](#)  
Detrended



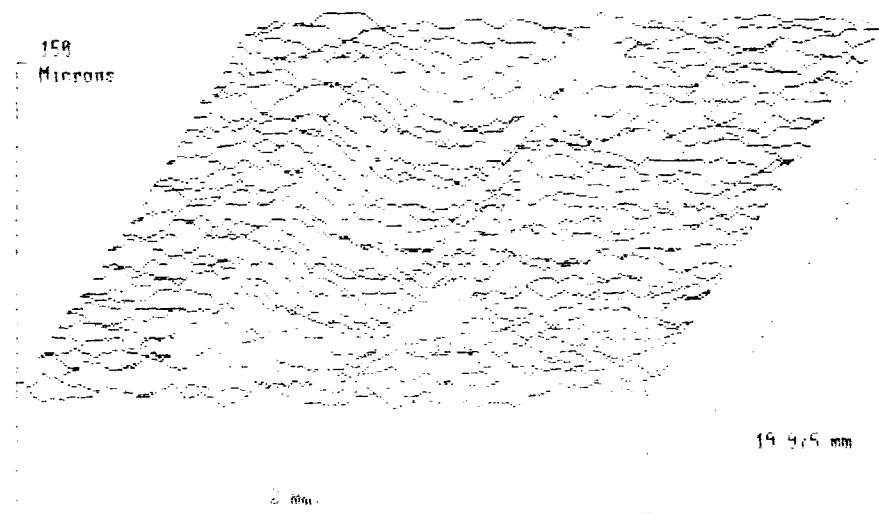
## HSSA 2: Hardened and Ground

Data from Lihssia Savard  
Retracted



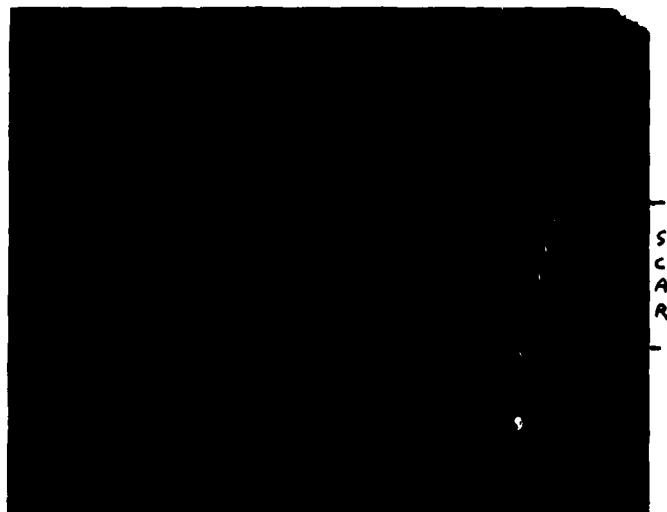
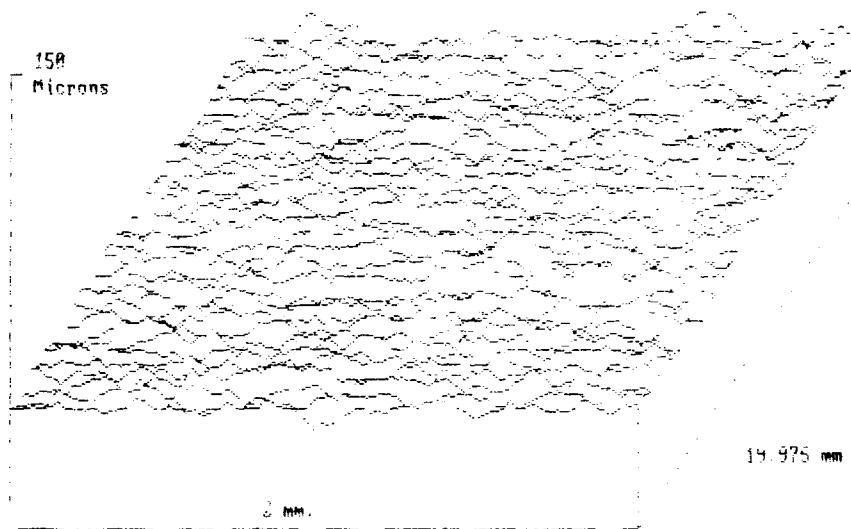
# HSSA3: Plasma Nitrocarburized 1

Data from bibone-2.dat  
Detrended



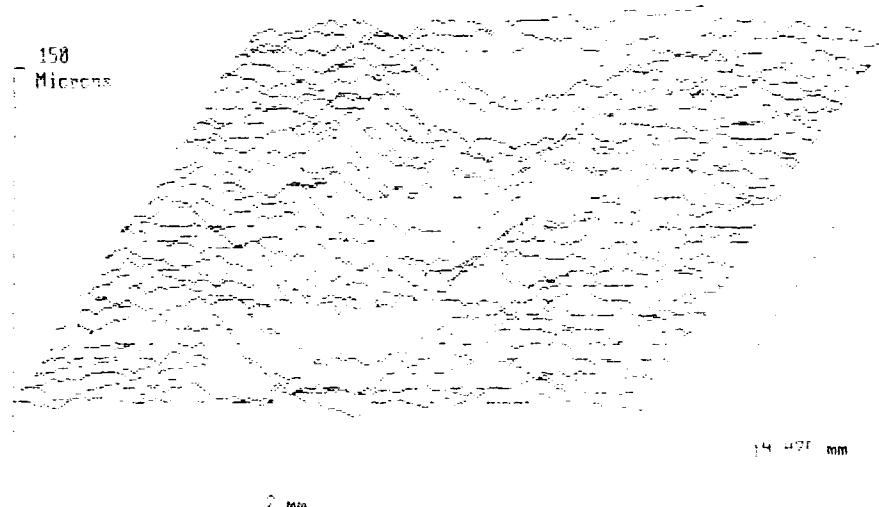
# HSSA4: Beta Nitrocarburized 1

Data from HSSA4.dat  
Detrended



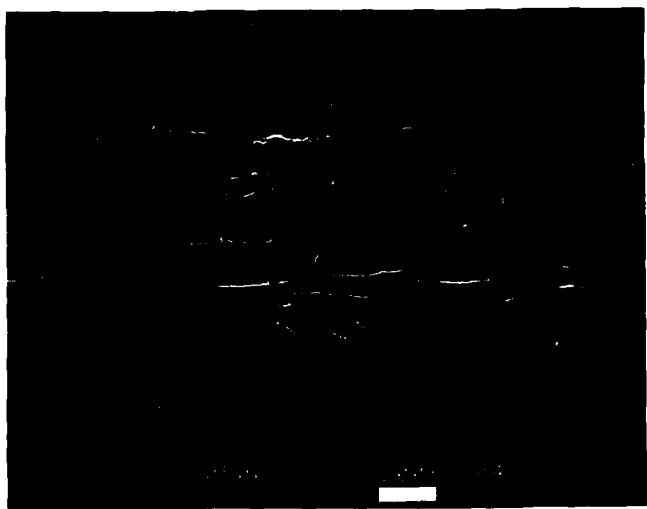
# HSSA5: Ion Implanted 1

Data from HSSA-5.dat  
Decrended



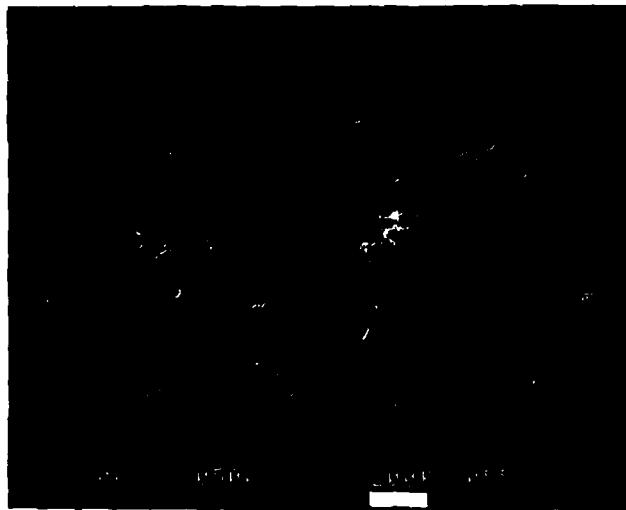
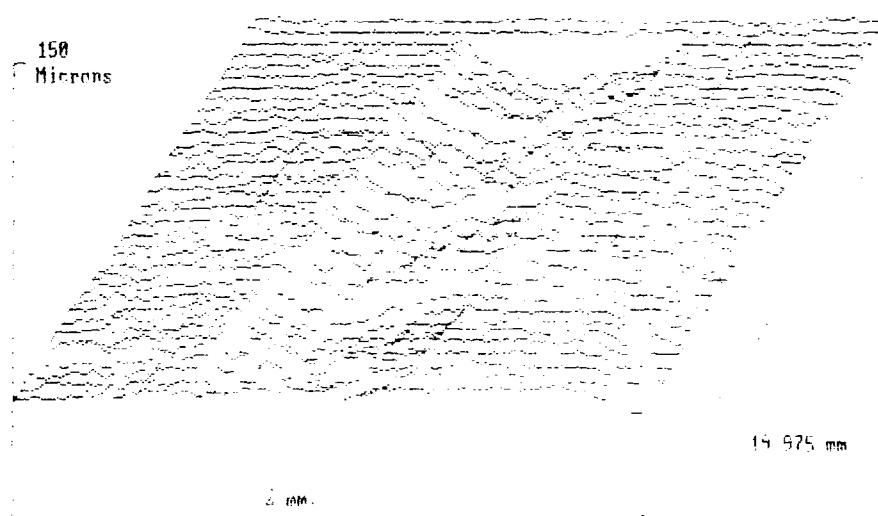
# HSSA 6: Ion Implanted 2

Data from b:hssa-6.dat  
Detrended



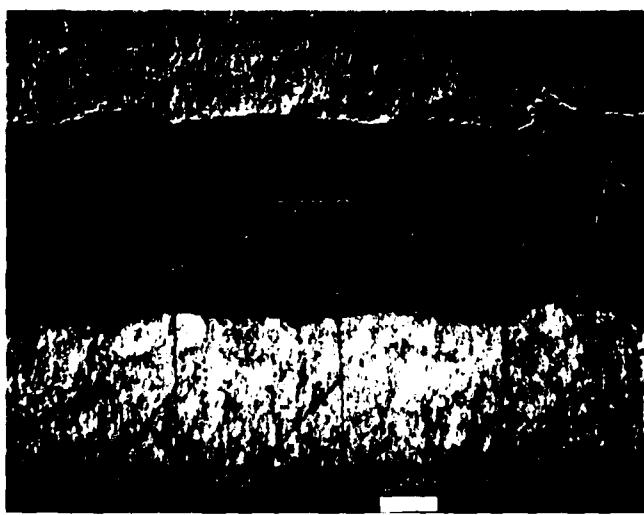
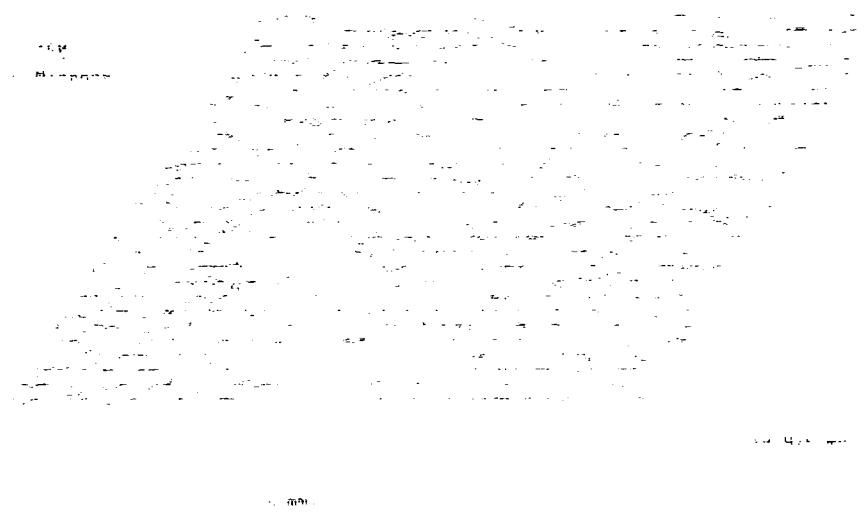
# HSSA7: Hard Anodised 1

Data from HSSA7.dat  
Detrended



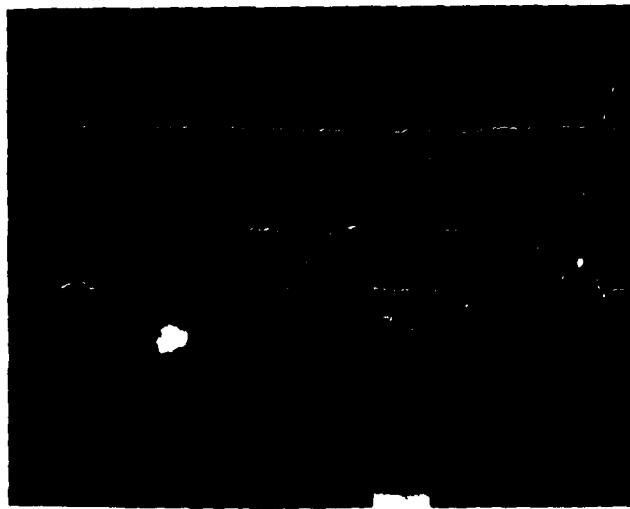
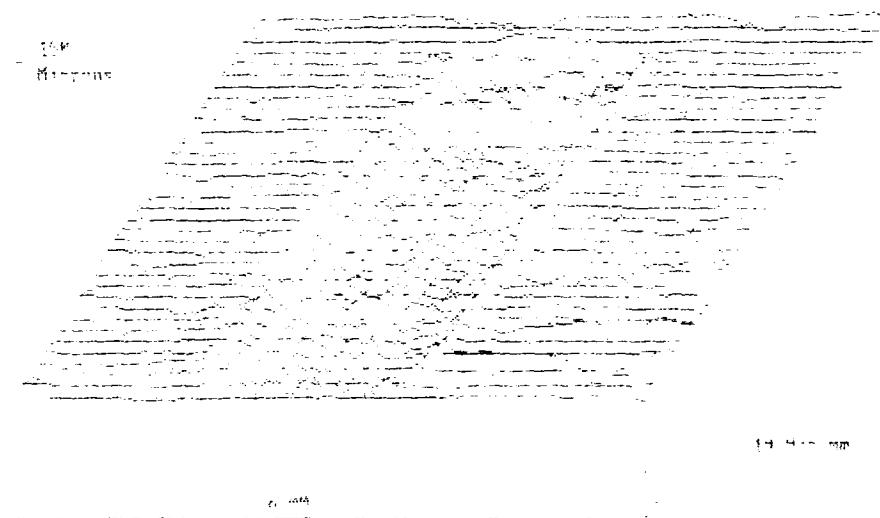
# HSSA8: Hard Anodised 2

Data from HSSA8.dat  
Interpolated



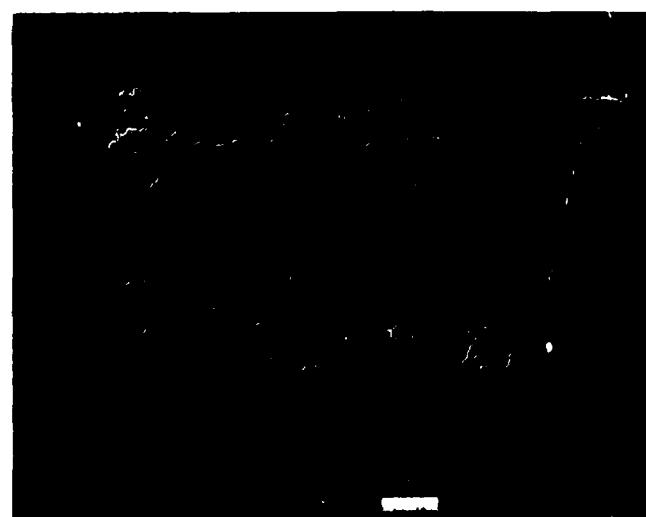
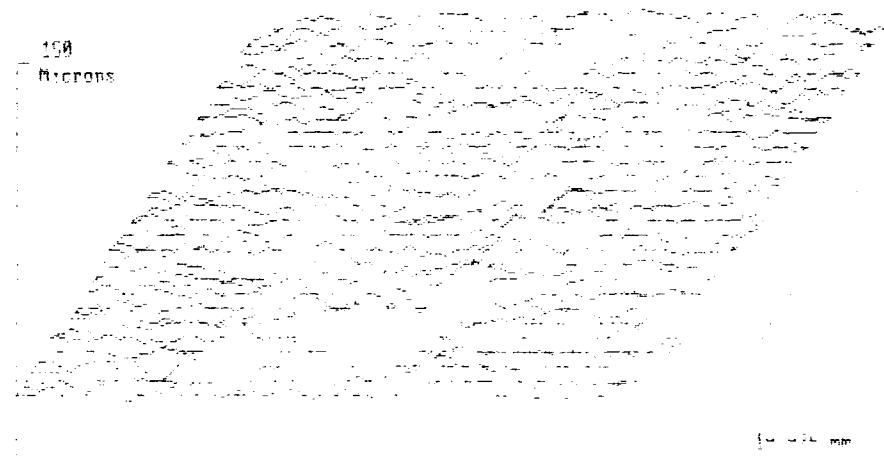
# HSSA9: Plasma Nitrocarburized 2

Data from without Q-dat  
Detached



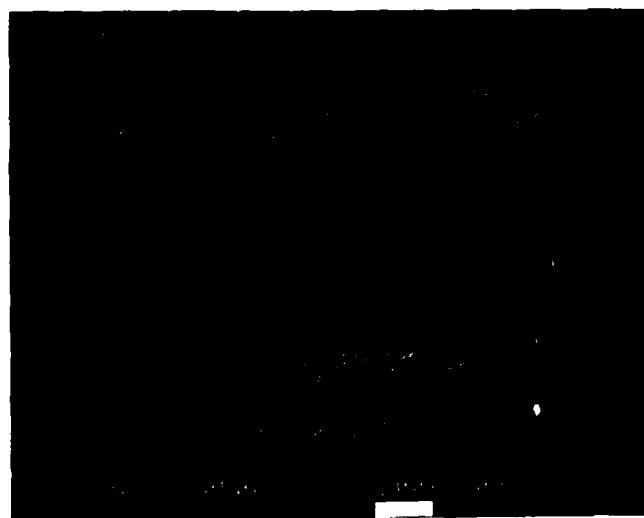
# HSSA 10: Hard Anodised 3

Data from Ulisesa 19.dat  
Scanned



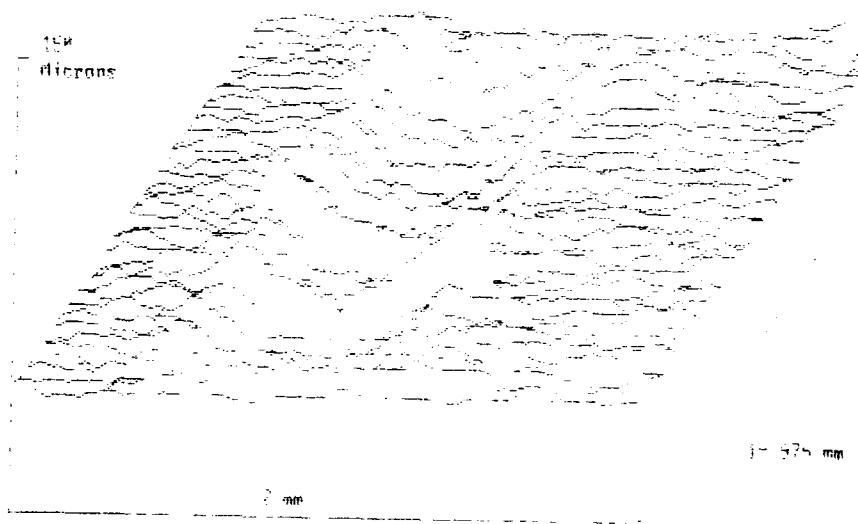
# HSSA II: Hard Anodised 4

Data from bithssa-11.dat  
Detrended



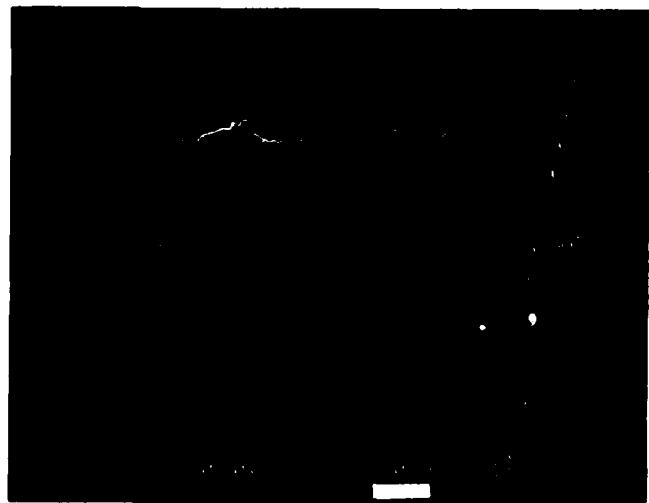
# HSSA 12: Plasma Nitrided 1

Data from h:hssa-12.dat  
Detrended



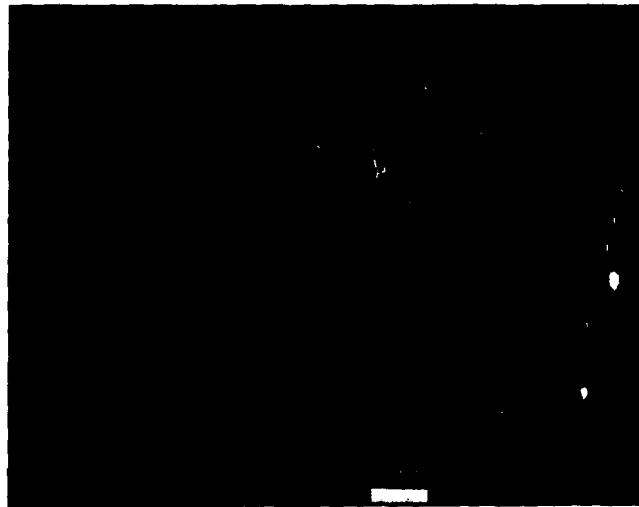
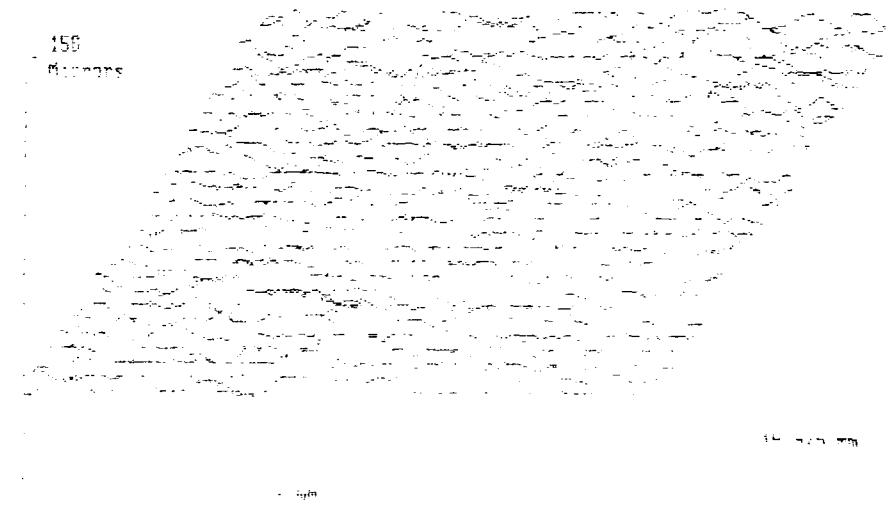
# HSSA 13: Plasma Nitrided 2

Date from hssa 13.dat  
Detected



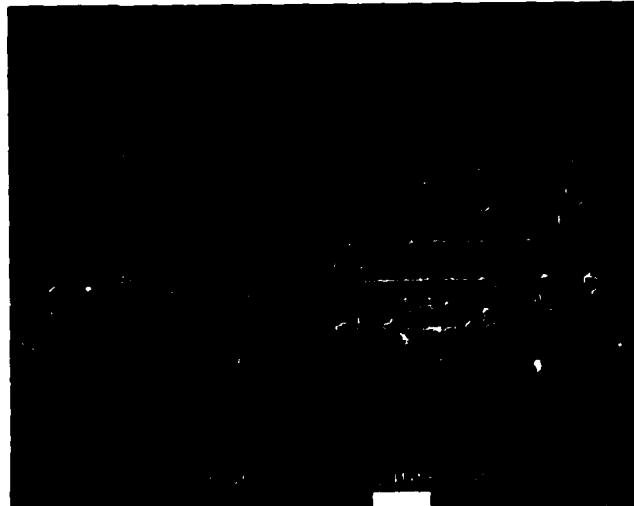
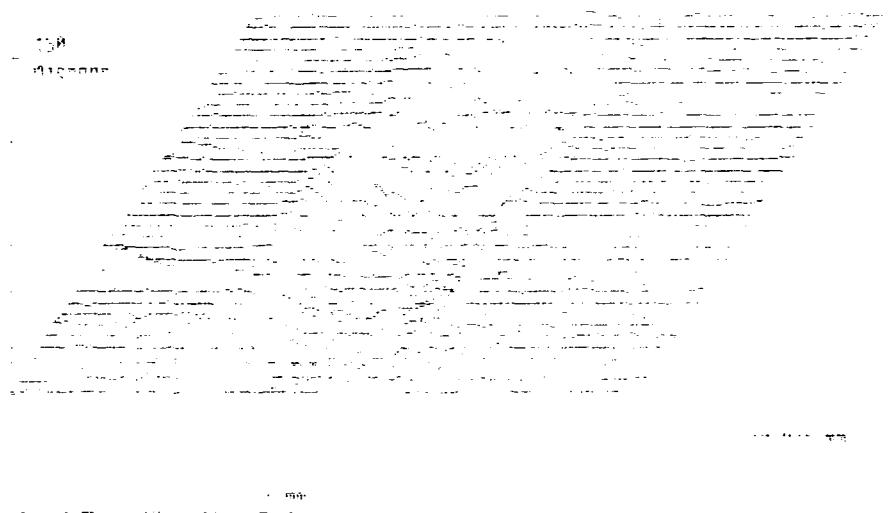
# HSSA 14: High Temperature Nitrocarburized 1

Scanned from Micrograph 14.tif  
200x1000



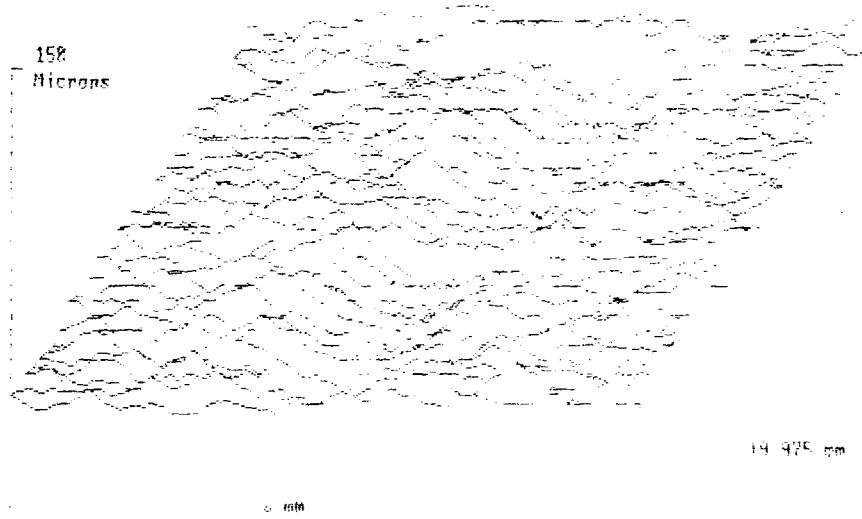
# HSSA15: Nitrosc 1

Data from Ethane 10.dat  
Retracted



# HSSA 17: Nitroso 2

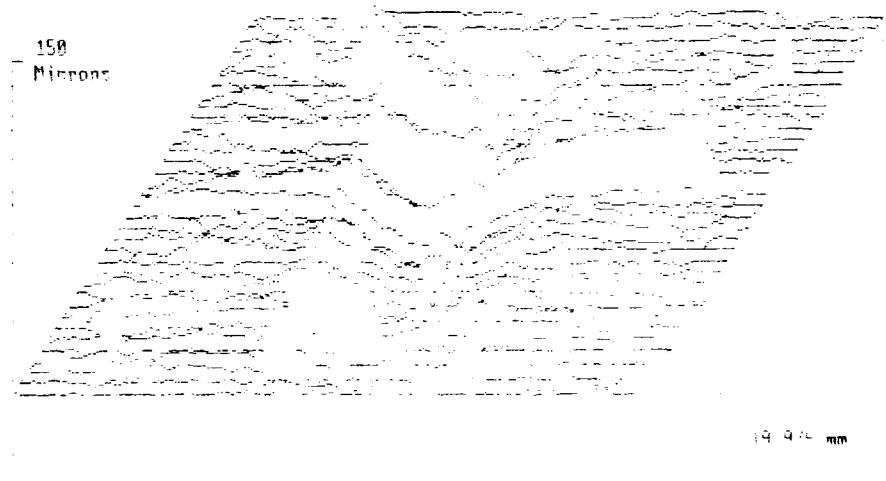
Data from bithesa-17.dat  
Detrended



# HSSA 18: Nitroce 3

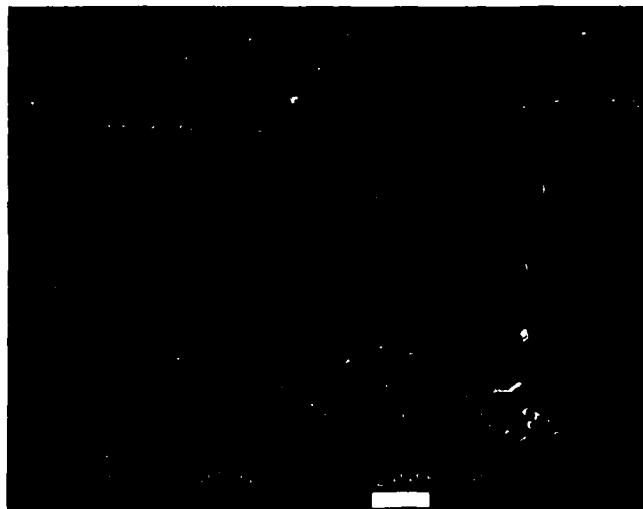
Data from b:hssa-18.dat

Detailed



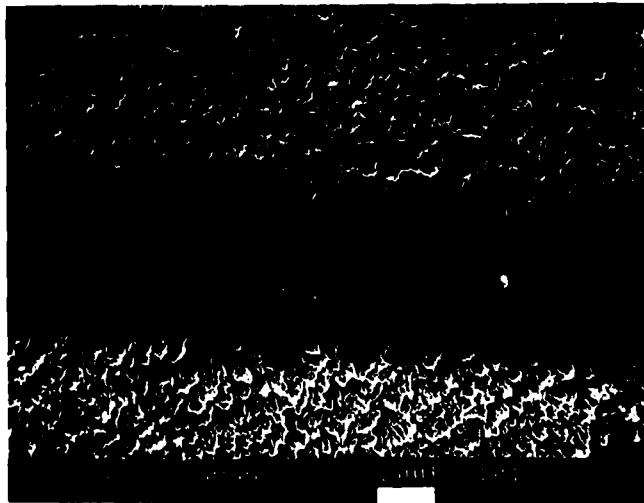
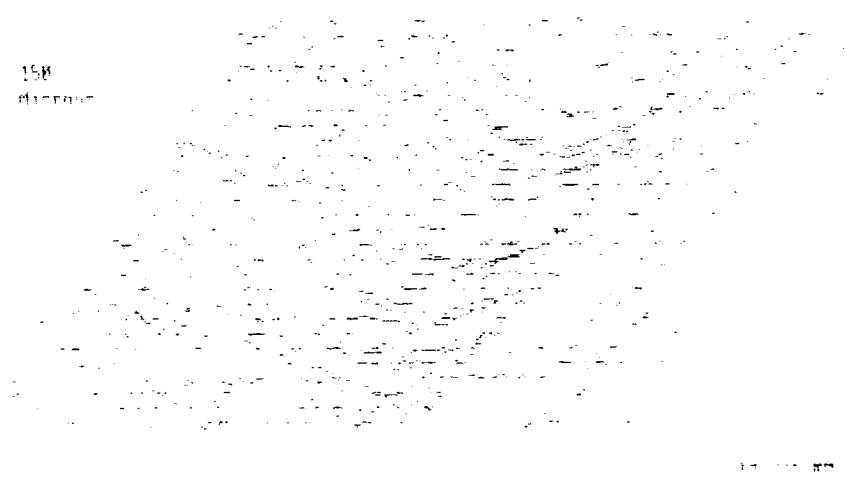
14.94 mm

2 mm



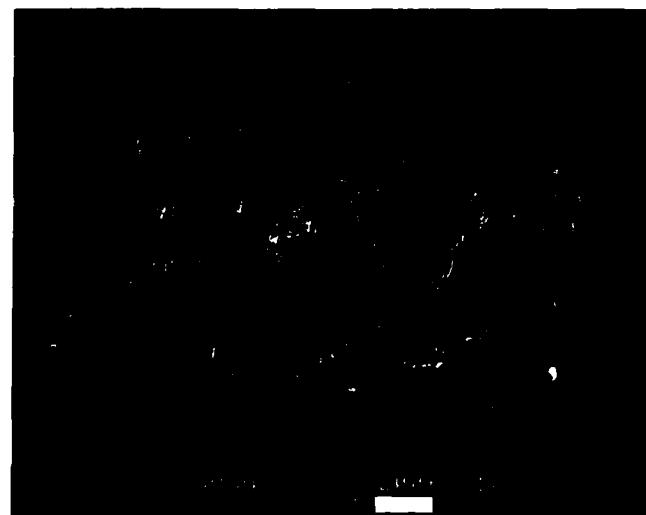
# HSSA 19: Pack Aluminising 2

Data from hbase 19.dat  
Datrenden



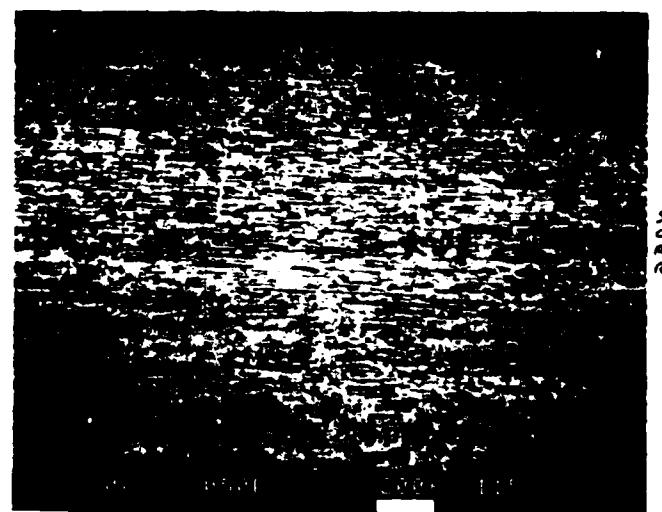
# HSSA 20: Gas Carbonitriding 1

Data from Ithaca 20.dat  
Detrended



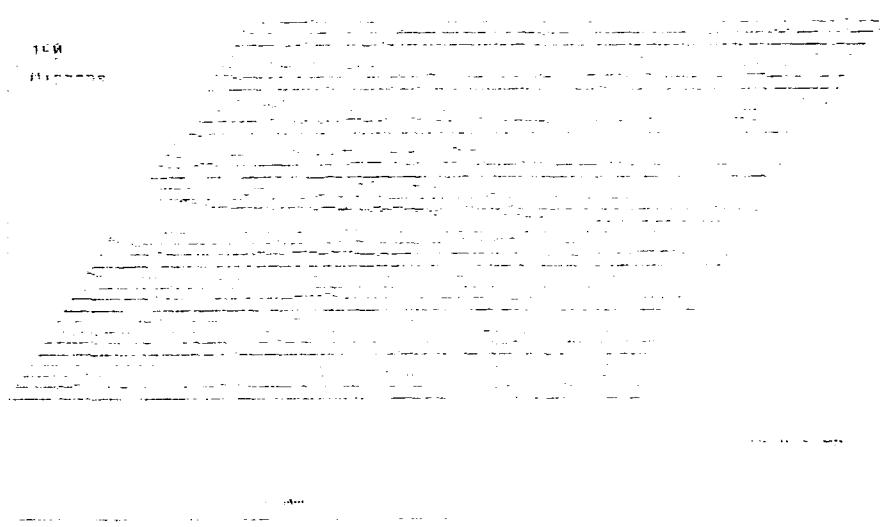
# HSSA 21: Diamond-like Carbon 1

Data from HSSA-21.dat  
Not scaled

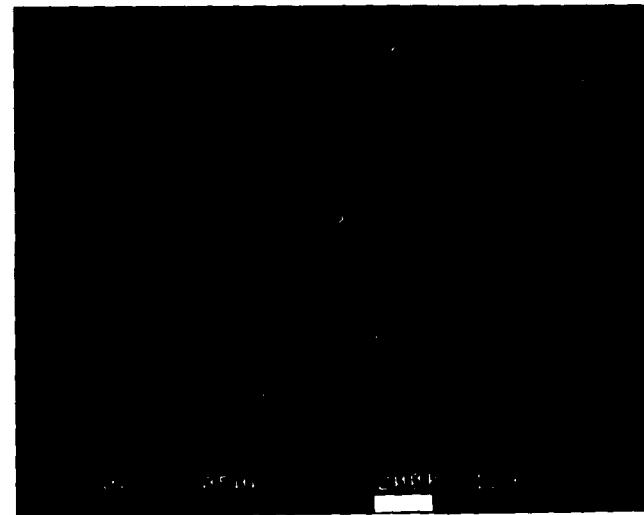


# HSSA 22: TiN Reactive Sputter

Data from 11/26/01  
Continued



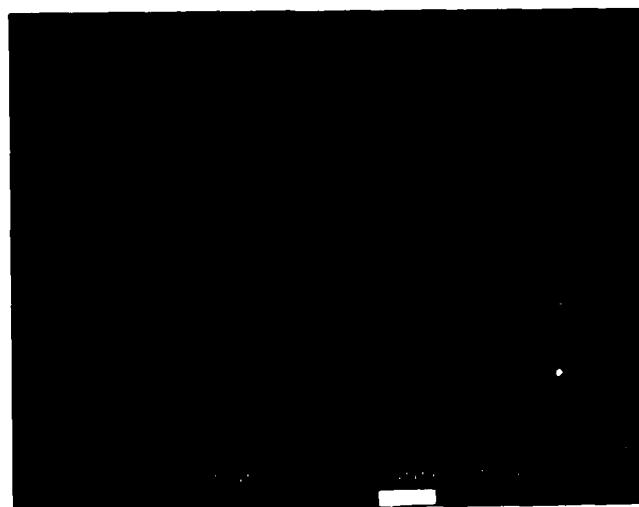
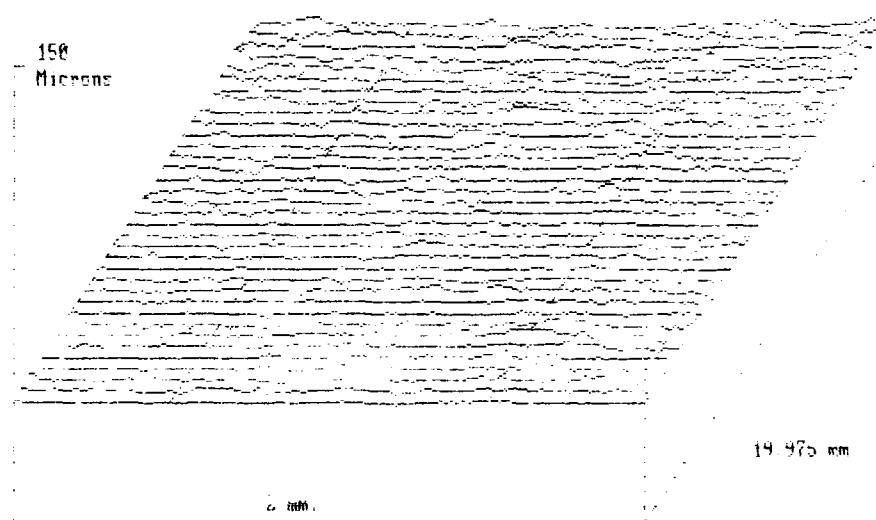
Scanning electron micrograph of the sputtered film.



Scanning electron micrograph of the sputtered film.

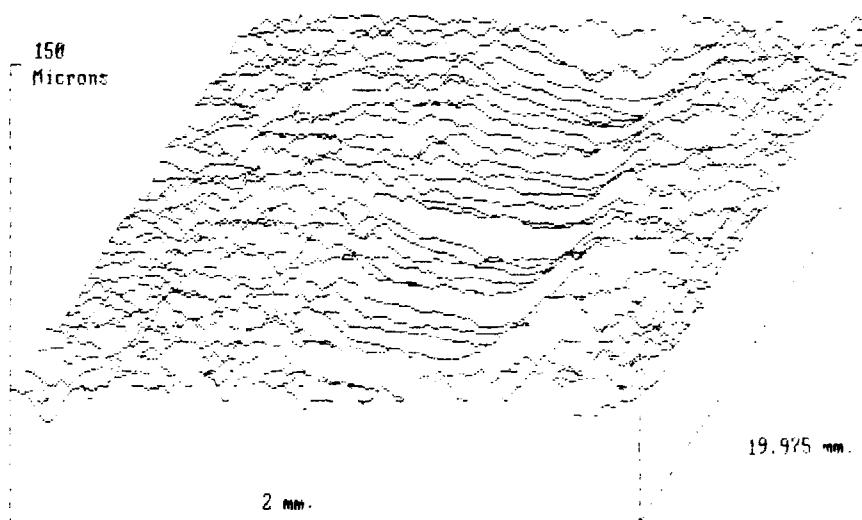
# HSSA 23: TiN/HfN Multilayer

Data from HSSA-23.dat  
Detrended

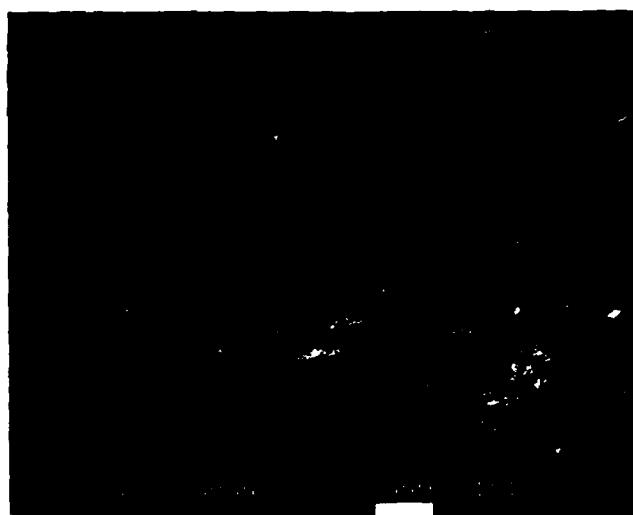


# HSSA 24: Pack Aluminising 3

Data from b:hssa-24.dat  
Detrended



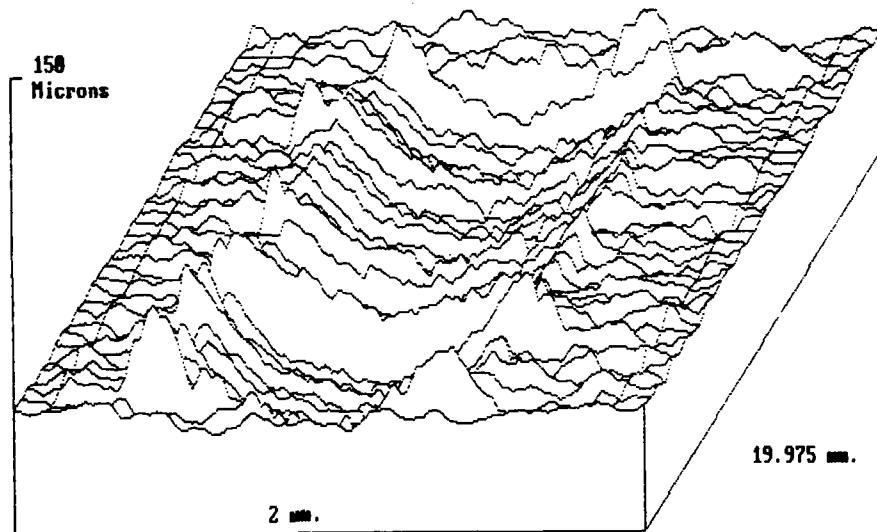
Scanning Micrograph of the same area  
Polarized light  
X = 19.975 mm Y = 2 mm Z = 150 microns



**APPENDIX 5: 50N Wear Profiles and SEM Micrographs of Wear Tracks**

# HSSA1: Solution Heat Treated

Data from b:hssa1.dat  
Detrended

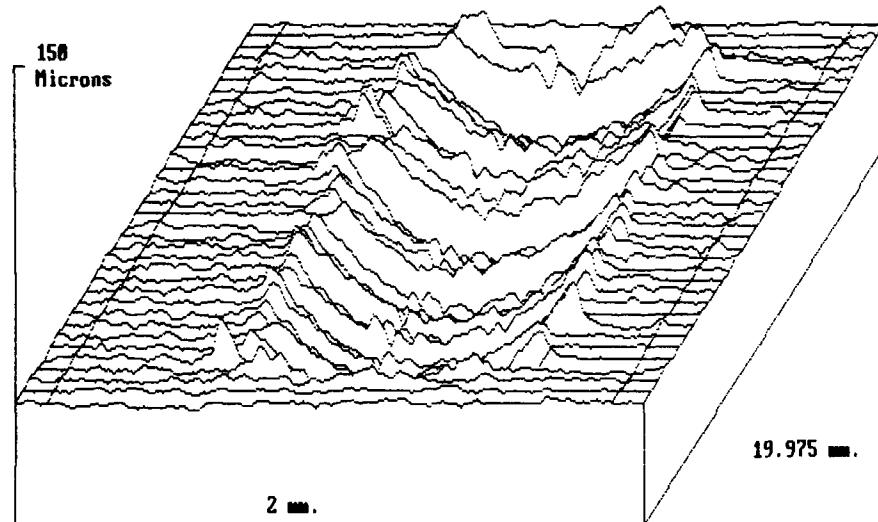


Wear volume in cubic millimetres  
Above datum      Below datum      Net loss  
.0456357      .2335793      .1879436

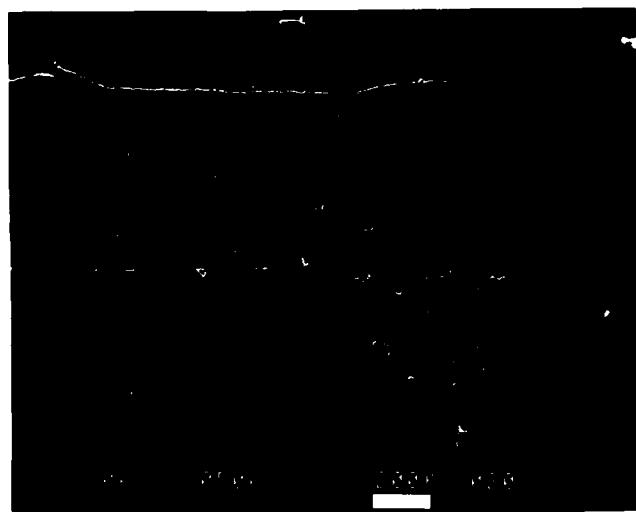


## HSSA2: Hardened and Ground

Data from b:hssa2.dat  
Detrended

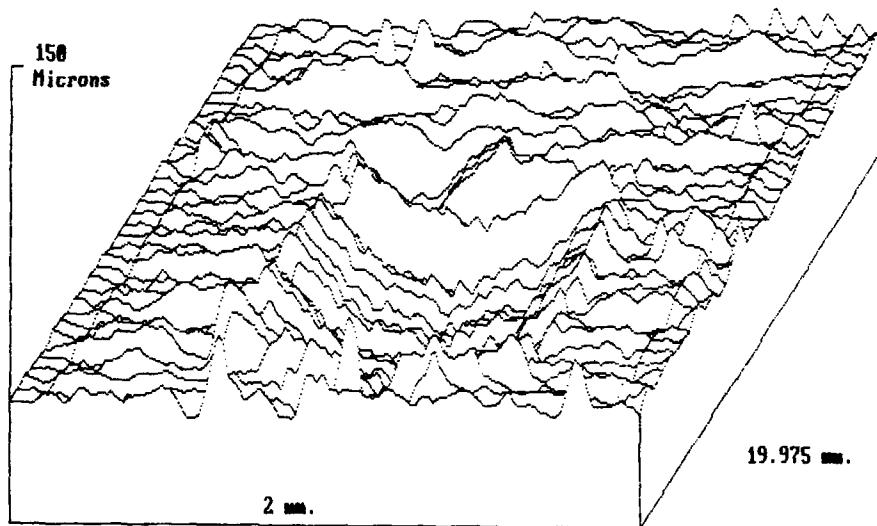


Wear volume in cubic millimetres  
Above datum      Below datum      Net loss  
1.857176E-02      .2437241      .2251523

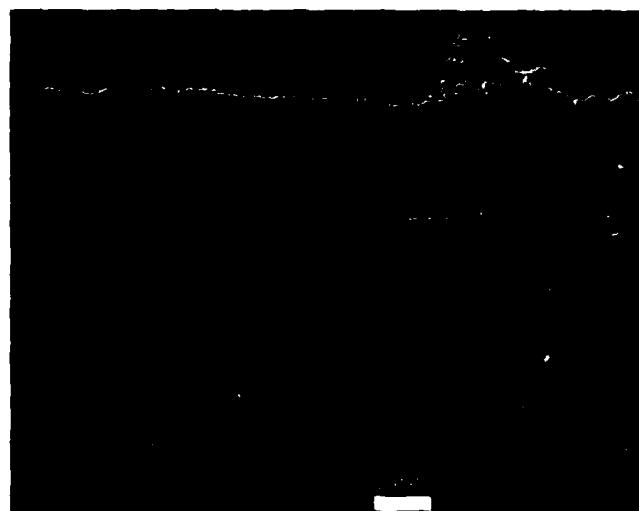


# HSSA3: Plasma Nitrocarburized 1

Data from b:hssa3.dat  
Detrended



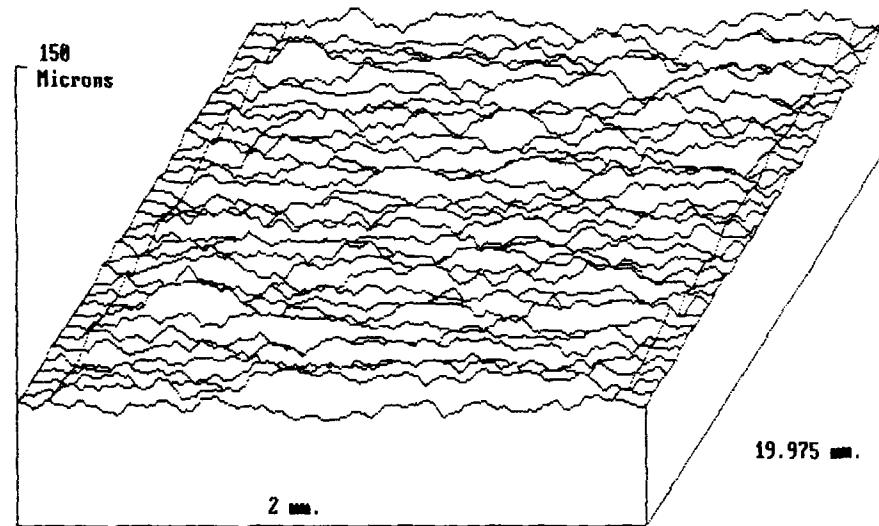
Wear volume in cubic millimetres  
Above datum      Below datum      Net loss  
5.616054E-02      .1875458      .1313852



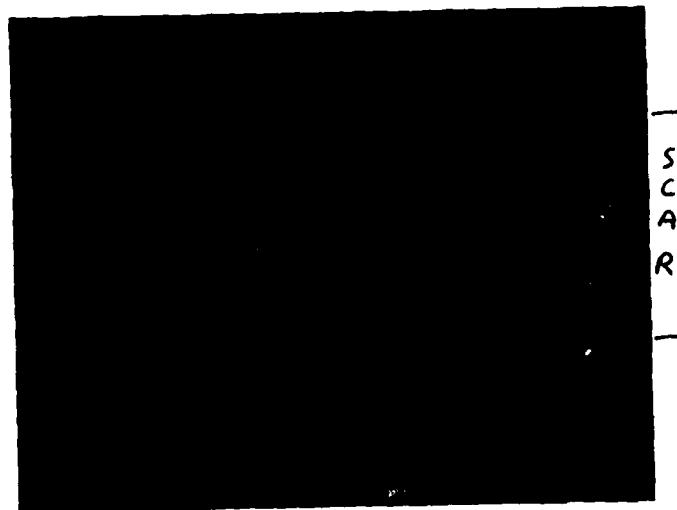
# HSSA4: Beta Nitrocarburized 1

Data from b:hssa4.dat

Betrended

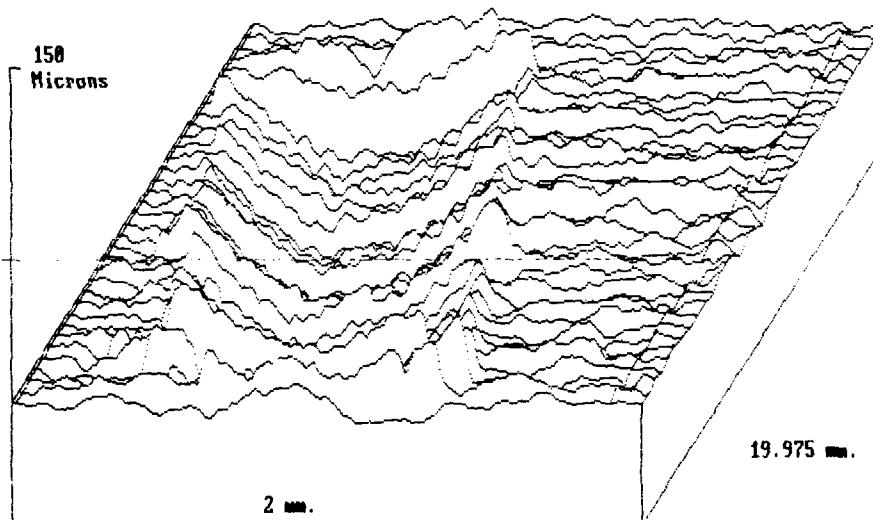


Wear volume in cubic millimetres  
Above datum      Below datum      Net loss  
3.921508E-02    3.531782E-02    -3.897257E-03

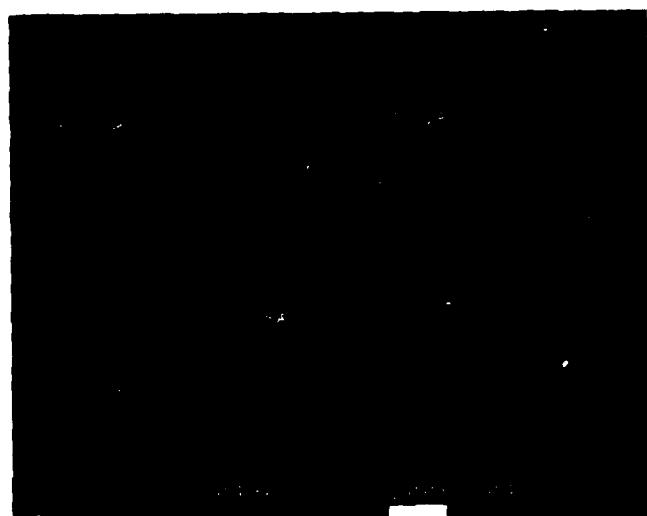


# HSSA 5: Ion Implanted 1

Data from b:hssa5.dat  
Detrended

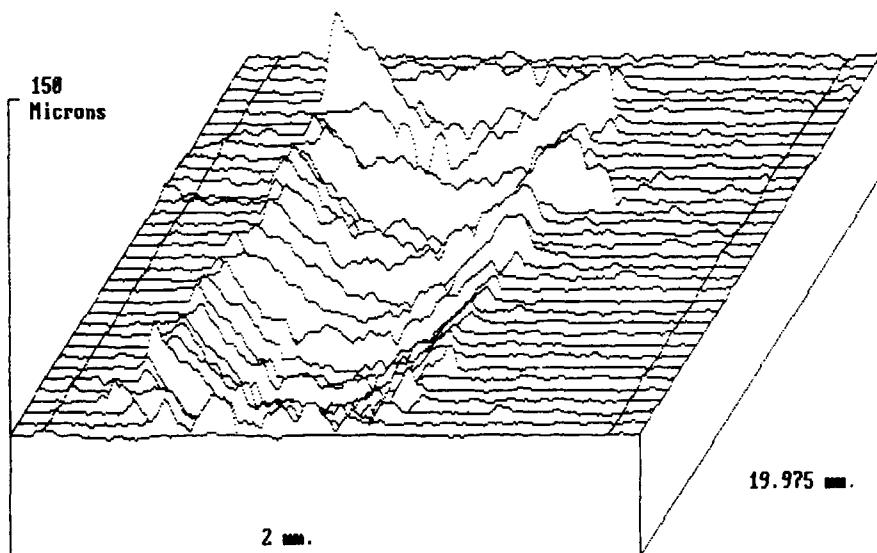


Wear volume in cubic millimetres  
Above datum      Below datum      Net loss  
4.209065E-02    .2399547       .1978641

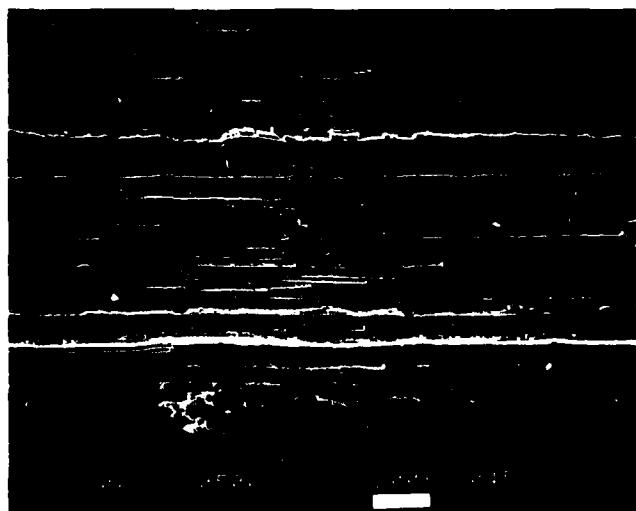


# HSSA 6: Ion Implanted 2

Data from b:hssa6.dat  
Detrended

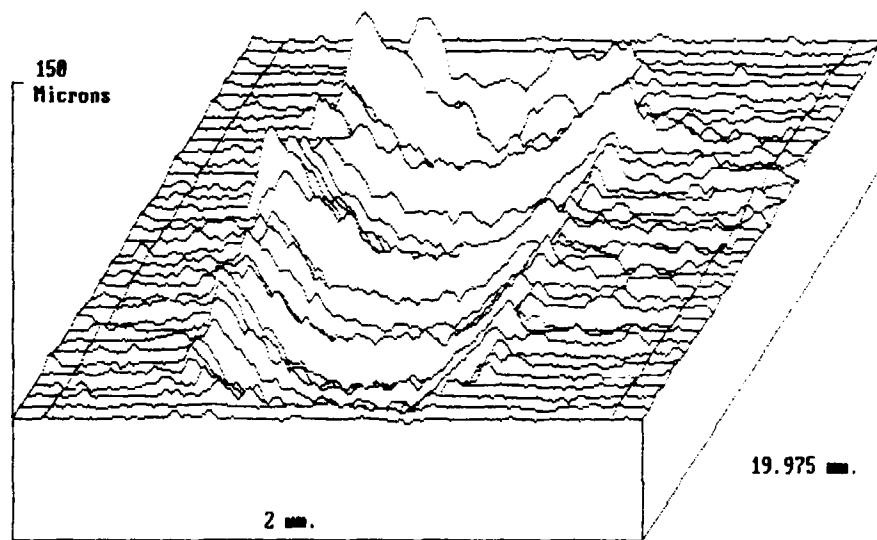


Wear volume in cubic millimetres  
Above datum      Below datum      Net loss  
2.041939E-02    .2303723      .2099529

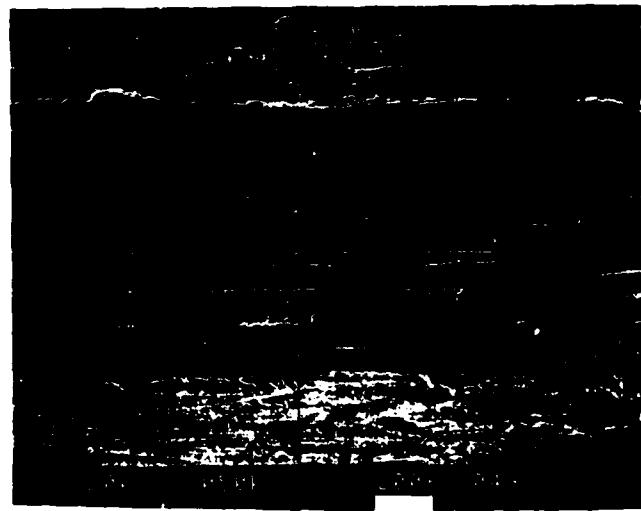


# HSSA7: Hard Anodised 1

Data from b:hssa7.dat  
Detrended

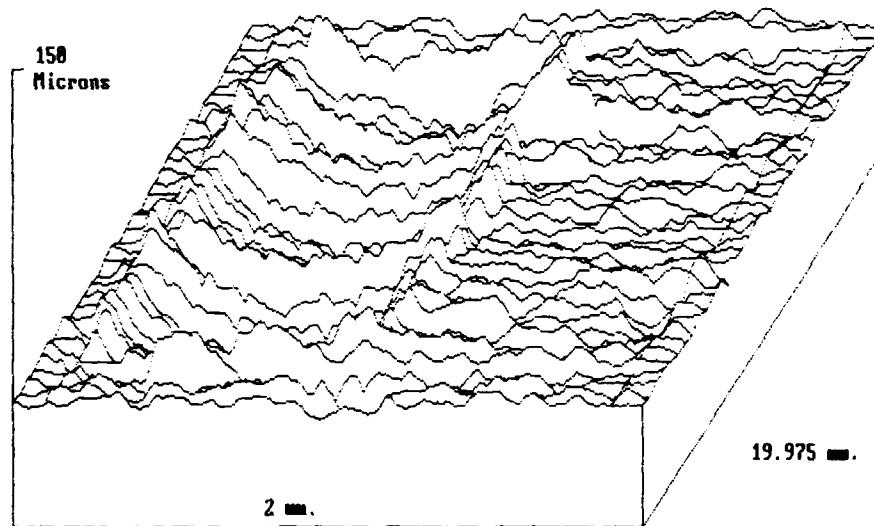


Wear volume in cubic millimetres  
Above datum      Below datum      Net loss  
2.642487E-02      .2412461      .2148212

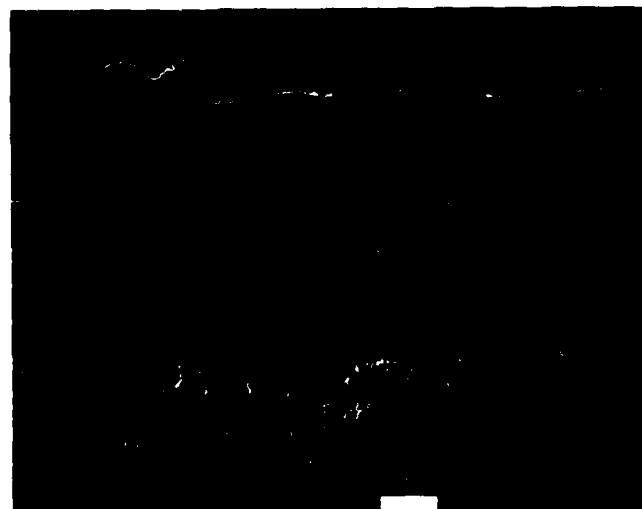


# HSSA8: Hard Anodised 2

Data from b:hssa8.dat  
Detrended

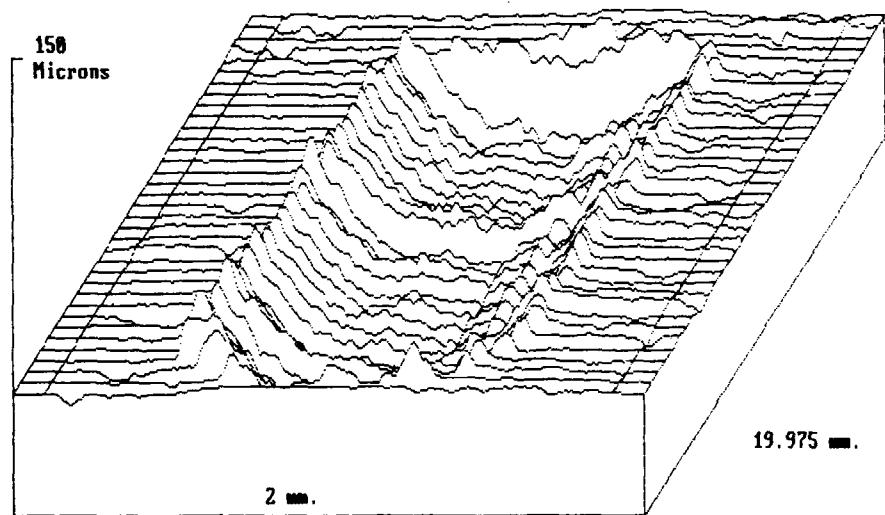


Wear volume in cubic millimetres  
Above datum      Below datum      Net loss  
4.153366E-02      .2389727      .197439

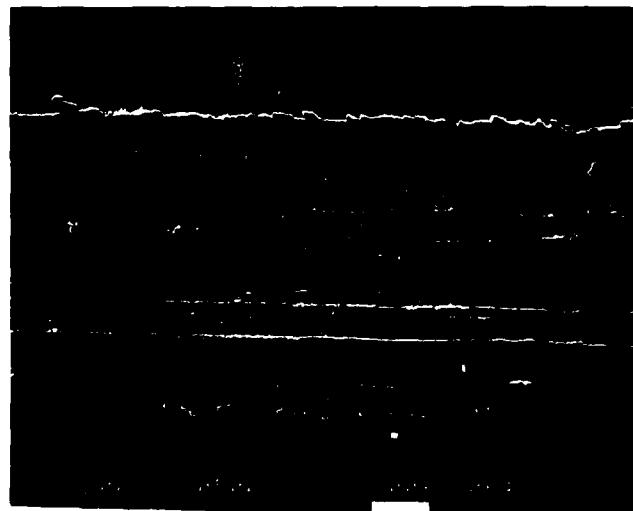


# HSSA9: Plasma Nitrocarburized 2

Data from b:hssa9.dat  
Detrended

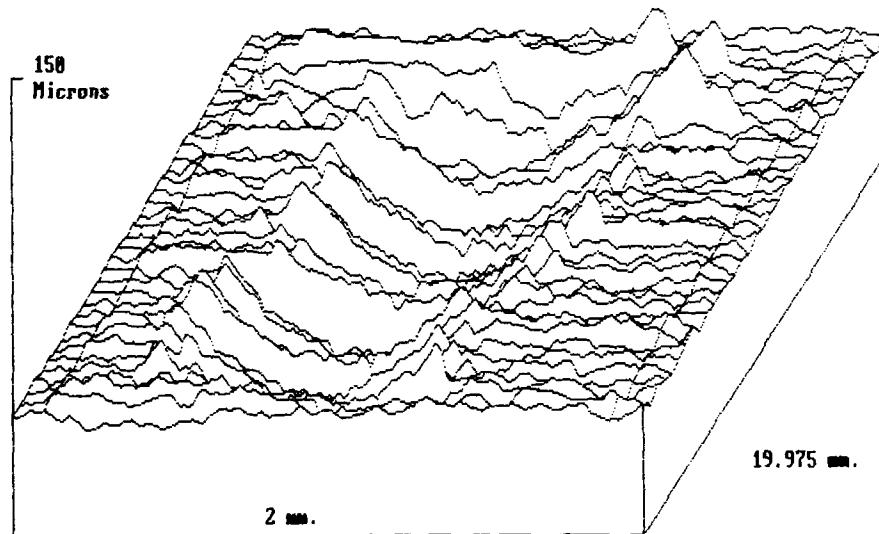


Wear volume in cubic millimetres  
Above datum      Below datum      Net loss  
2.866068E-02      .255984      .2273234

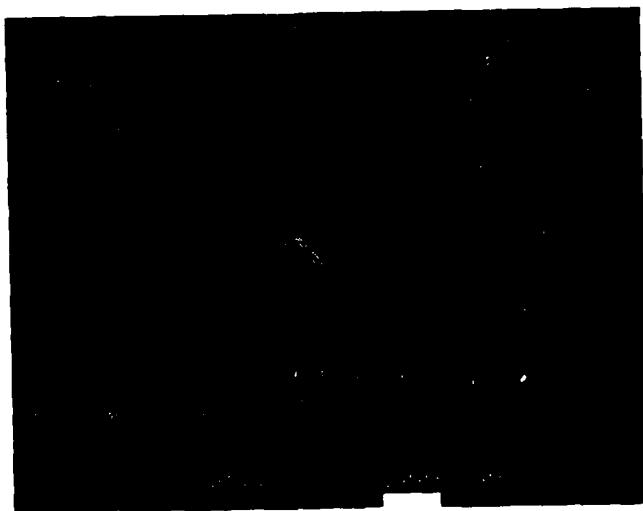


# HSSA 10: Hard Anodised 3

Data from h:hssa10.dat  
Detrended

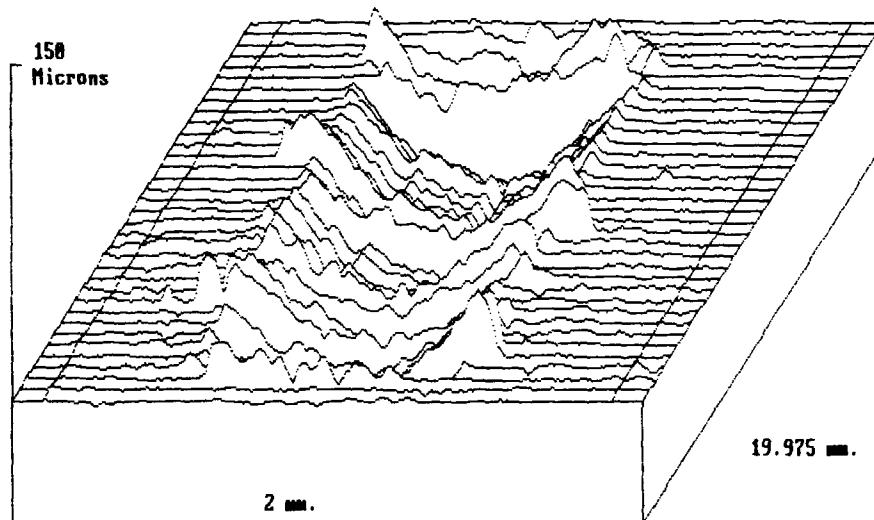


Wear volume in cubic millimetres  
Above datum      Below datum      Net loss  
3.669301E-02      .2553586      .2186656

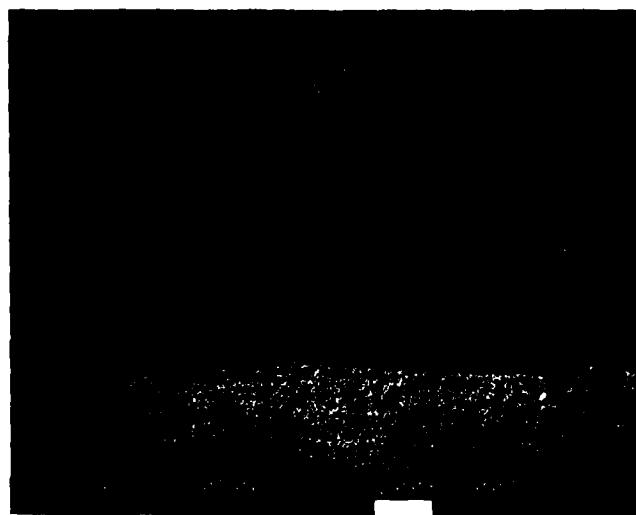


# HSSA 11: Hard Anodised 4

Data from b:hssa11.dat  
Detrended

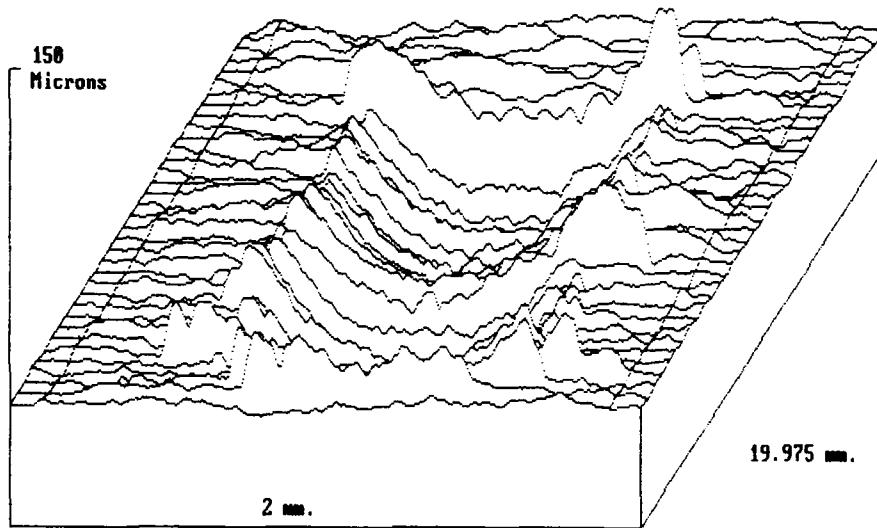


Wear volume in cubic millimetres  
Above datum      Below datum      Net loss  
2.775977E-02      .1922235      .1644637

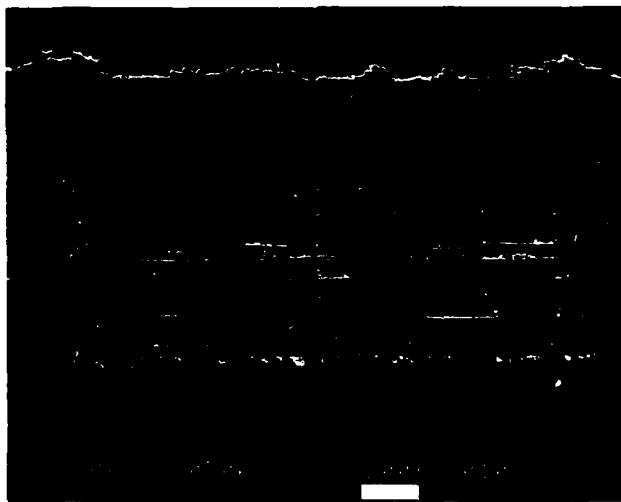


# HSSA 12: Plasma Nitrided 1

Data from hsssa12.dat  
Detrended

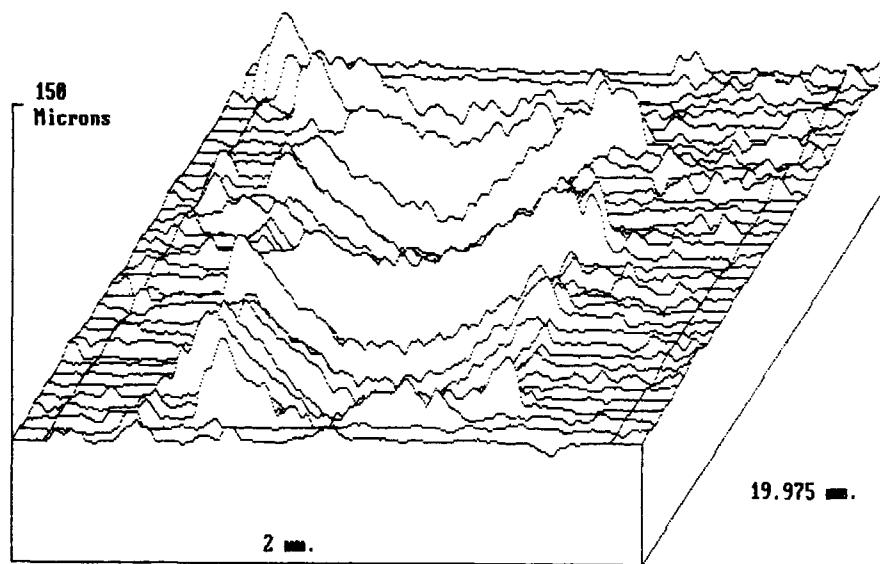


Wear volume in cubic millimetres  
Above datum      Below datum      Net loss  
5.554843E-02      .2511673      .1956188

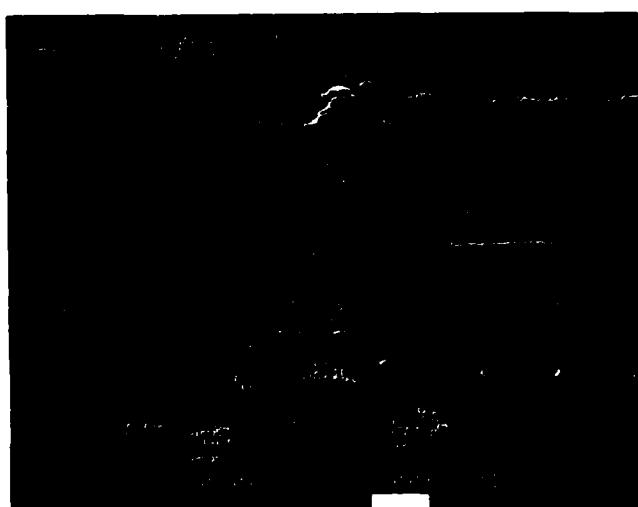


# HSSA13: Plasma Nitrided 2

Data from b:hssa13.dat  
Detrended



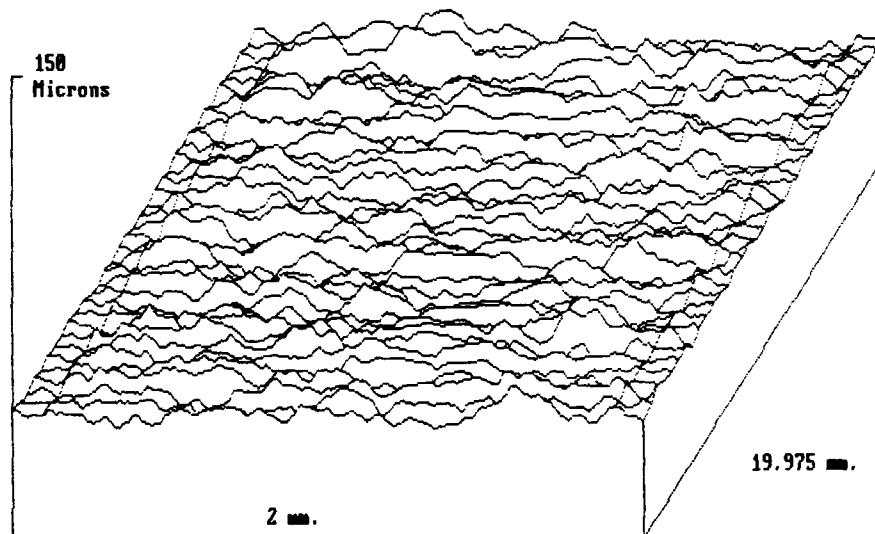
Wear volume in cubic millimetres  
Above datum      Below datum      Net loss  
4.008345E-02    .2619238      .2218404



# HSSA14: High Temperature Nitrocarburized 1

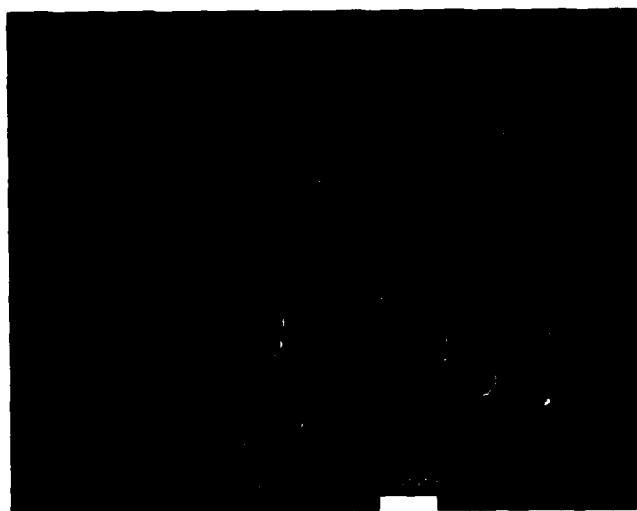
Data from b:hssa14.dat

Detrended



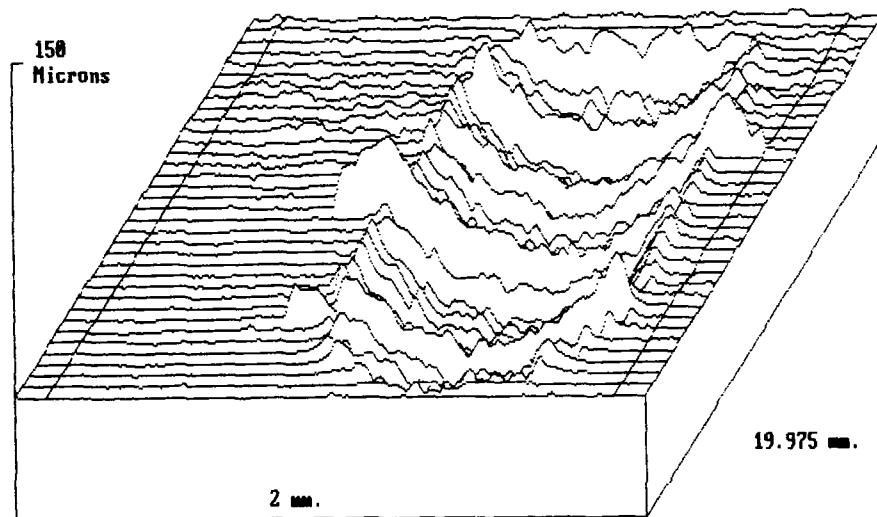
Wear volume in cubic millimetres

Above datum	Below datum	Net loss
4.902035E-02	4.254118E-02	-6.47917E-03

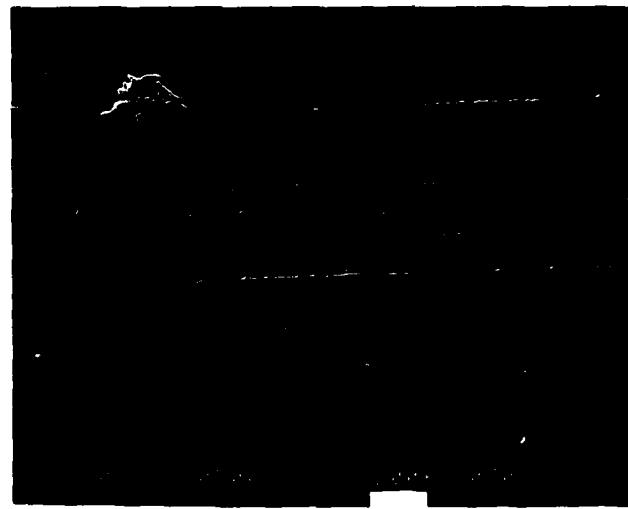


# HSSA 15: Nitrox 1

Data from b:hssa15.dat  
Detrended

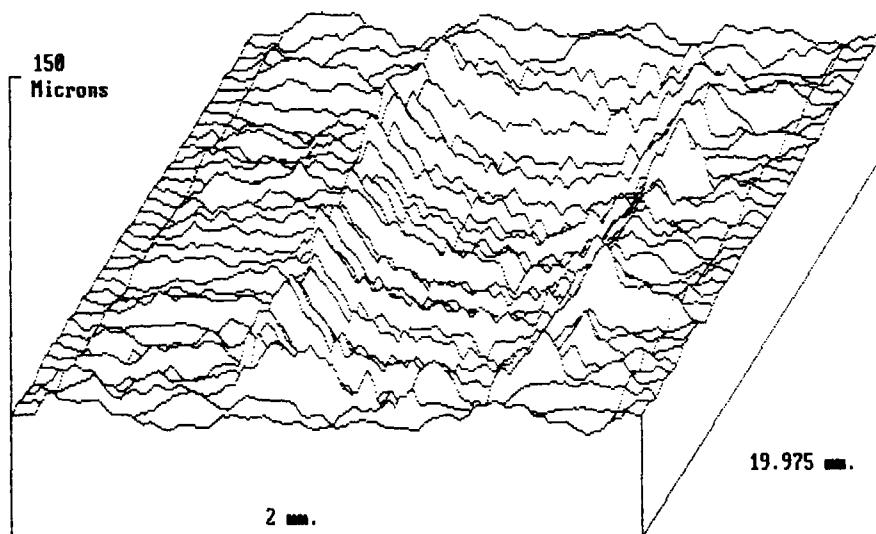


Wear volume in cubic millimetres  
Above datum      Below datum      Net loss  
1.879978E-02    .2240438      .205244

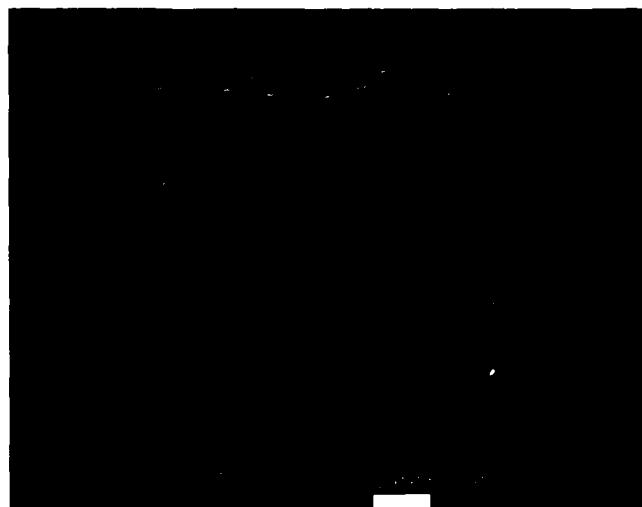


HSSA17: Nitroce 2

Data from h:hssa17.dat  
Detrended

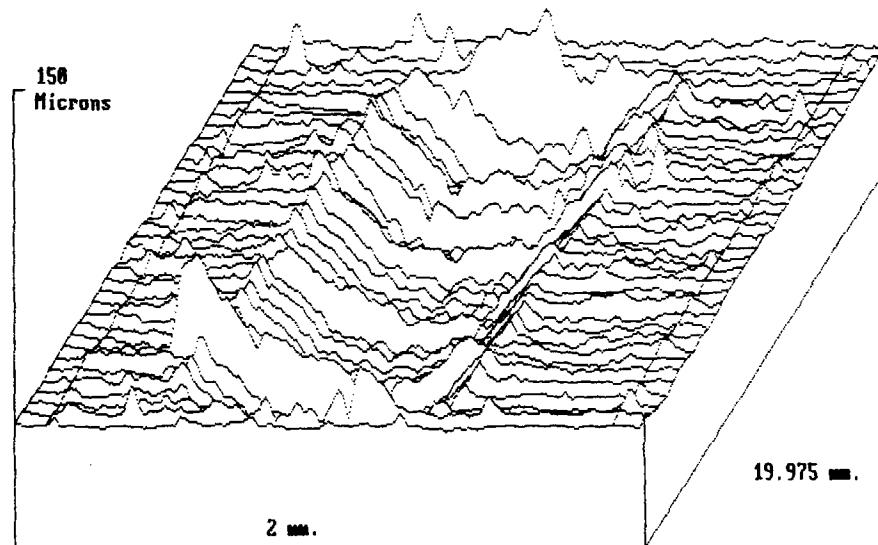


Wear volume in cubic millimetres  
Above datum      Below datum      Net loss  
4.378364E-02      .2352955      .1915119



# HSSA 18: Nitroce 3

Data from h:hssa18.dat  
Detrended

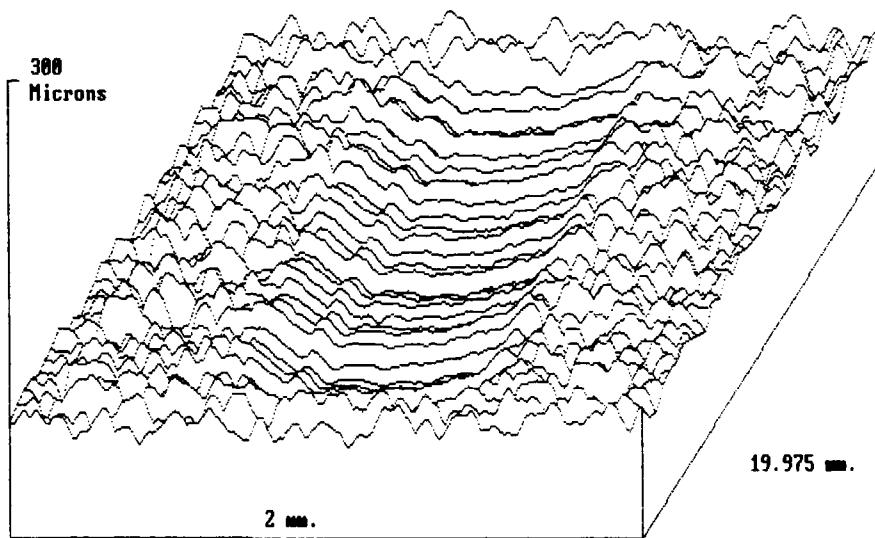


Wear volume in cubic millimetres  
Above datum      Below datum      Net loss  
2.324379E-02      .2662985      .2430547

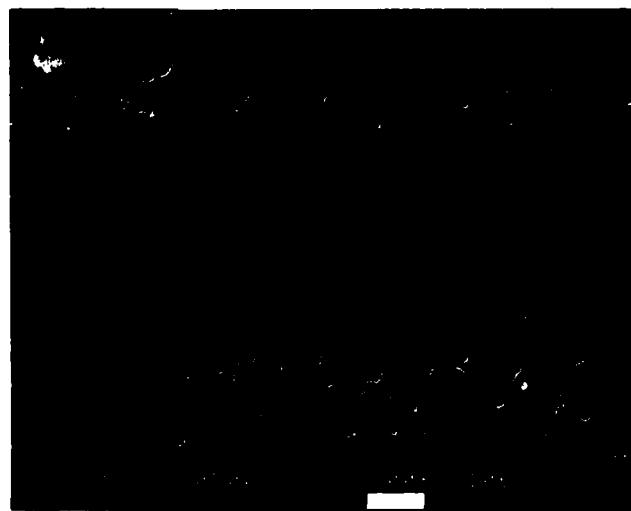


# HSSA19: Pack Aluminising 2

Data from b:hssa19.dat  
Detrended



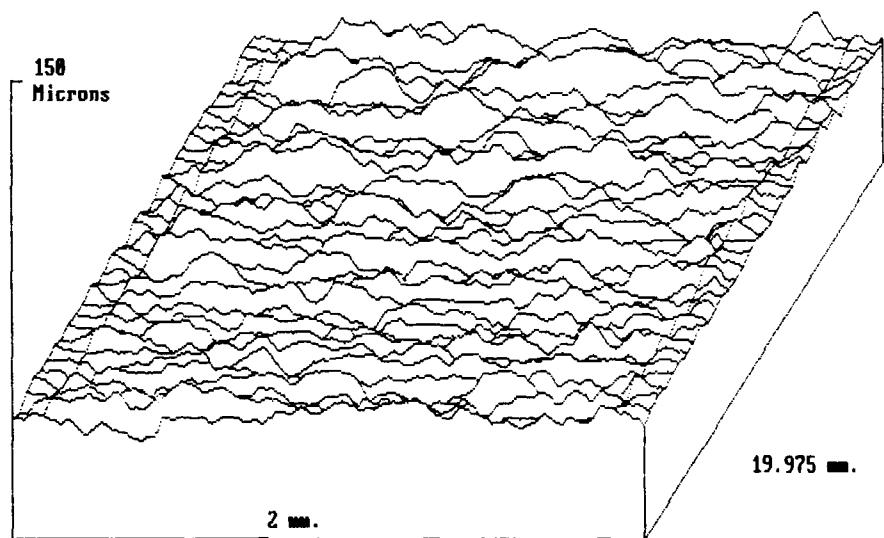
Wear volume in cubic millimetres  
Above datum      Below datum      Net loss  
7.481752E-02      .3003084      .2254909



# HSSA 20: Gas Carbonitriding 1

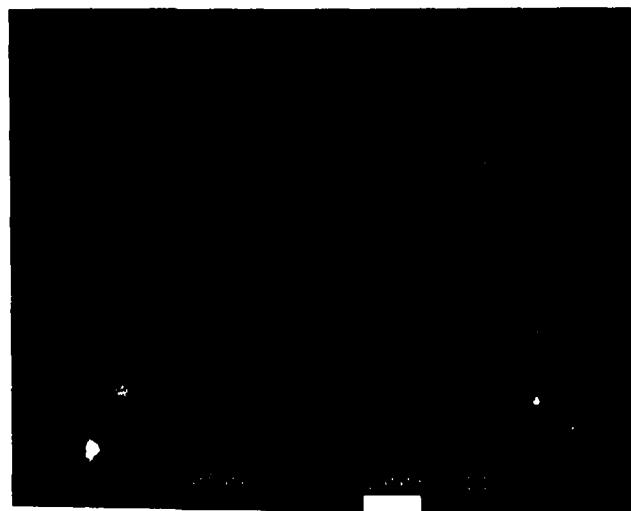
Data from b:hssa20.dat

Detrended



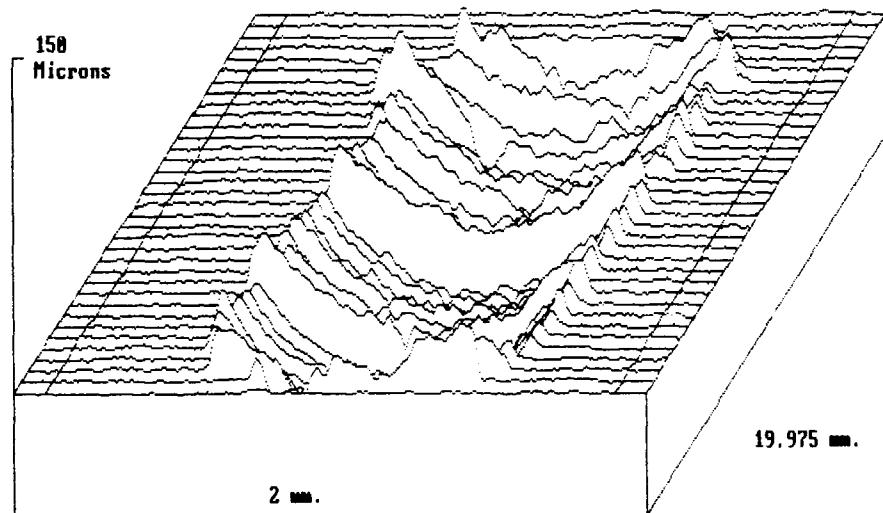
Wear volume in cubic millimetres

Above datum	Below datum	Net loss
4.566613E-02	5.848346E-02	1.281733E-02

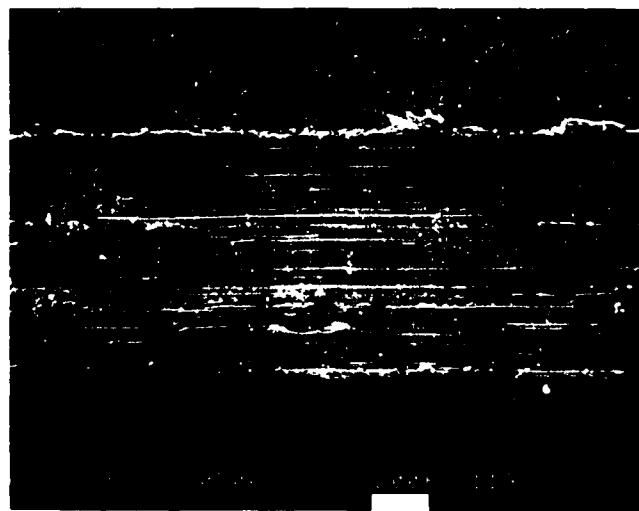


# HSSA 21: Diamond-like Carbon 1

Data from b:hssa21.dat  
Detrended

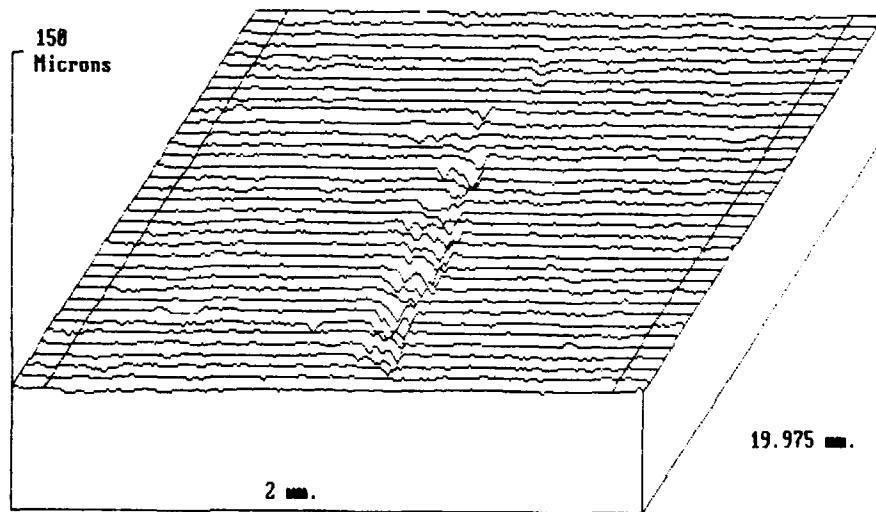


Wear volume in cubic millimetres  
Above datum      Below datum      Net loss  
2.667136E-02    .2495293       .222858

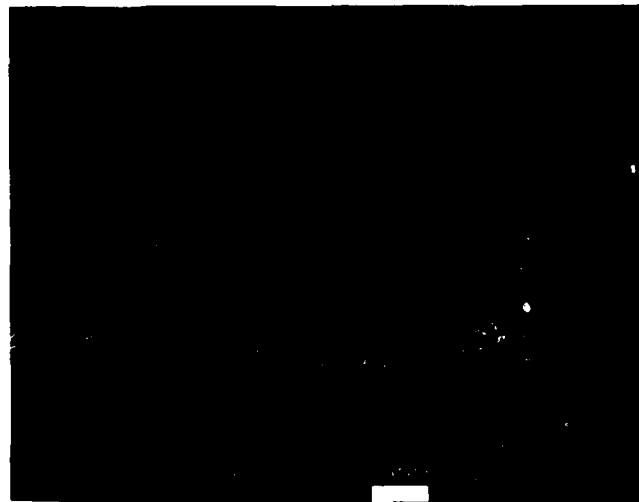


# HSSA 22: TiN Reactive Sputter

Data from b:hssa22.dat  
Detrended

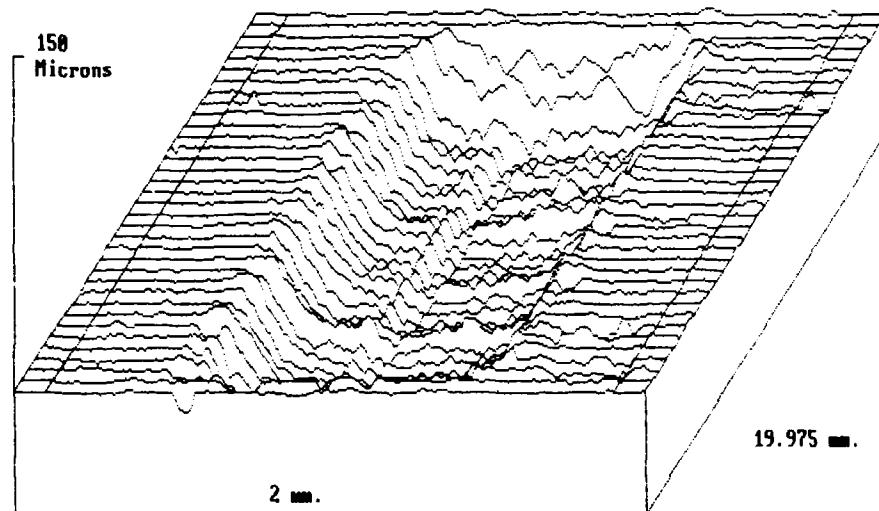


Wear volume in cubic millimetres  
Above datum    Below datum    Net loss  
3.728391E-03    1.470531E-02    1.097691E-02

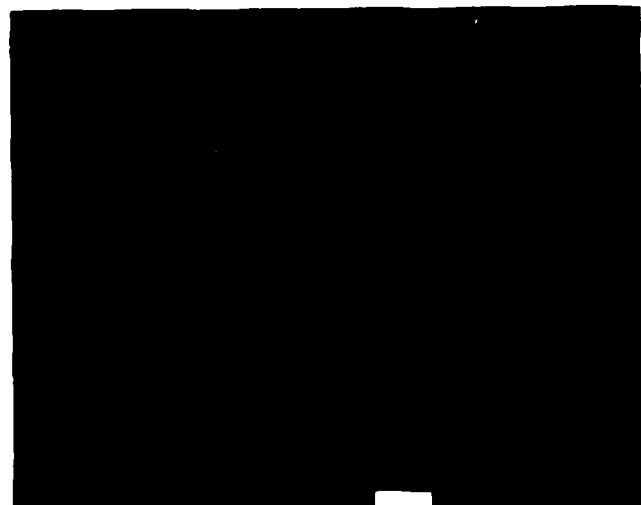


# HSSA 23: TiN/HfN Multilayer

Data from b:hssa23.dat  
Detrended

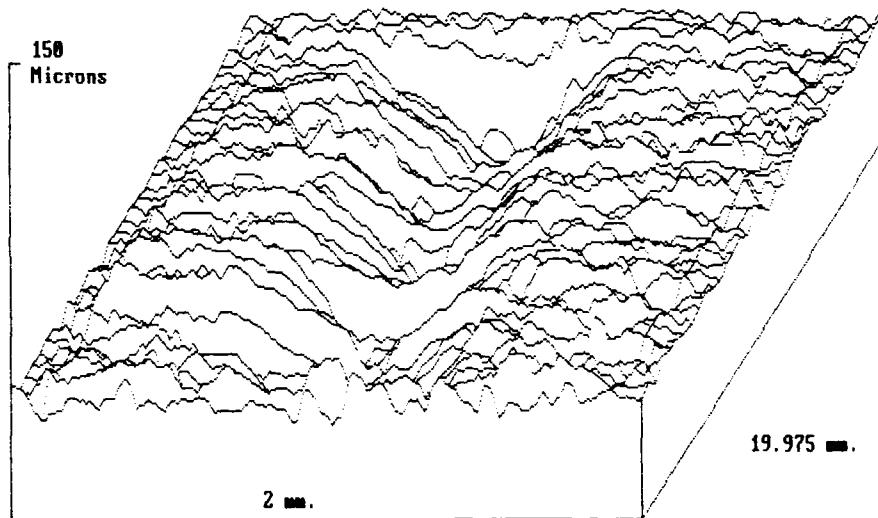


Wear volume in cubic millimetres  
Above datum      Below datum      Net loss  
4.79215E-03      .3629499      .3581578



# HSSA 24: Pack Aluminising 3

Data from b:hssa24.dat  
Detrended



Wear volume in cubic millimetres  
Above datum      Below datum      Net loss  
5.017138E-02      .2289717      .1788903

